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Universiteit Hasselt | Campus Diepenbeek | Agoralaan Gebouw D | BE-3590 Diepenbeek
Universiteit Hasselt | Campus Hasselt | Martelarenlaan 42 | BE-3500 Hasselt

2010
2011

GENEESKUNDE

master in de biomedische wetenschappen: klinische moleculaire wetenschappen

Masterproef

Movement analysis of uni- and bilateral functional tasks in healthy and neurologically disabled persons: a pilot study

Promotor :
Prof. dr. Peter FEYS

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Masterproef voorgedragen tot het bekomen van de graad van master in de biomedische wetenschappen , afstudeerrichting klinische moleculaire wetenschappen

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Table of contents

List of abbreviations

ADL:	Activities of daily living
ANOVA:	Analysis of variance
ARAT:	Action research arm test
AT:	Arm trainer
BIT:	Bilateral isokinematic training
CIMT:	Constraint-induced movement therapy
CNS:	Central nervous system
CP:	Cerebral palsy
CVA:	Cerebrovascular accident
DIR:	Direction
ES:	Electrical stimulator
EXE:	Execution
9HPT:	Nine hole peg test
ICC:	Intraclass correlation coefficient
ICF:	International Classification of Functioning, Disability and Health
IPA:	Impact on participation and autonomy
LQ:	Laterality quotient
MAL:	Motor activity log
MI:	Motricity index
MS:	Multiple sclerosis
PwMS:	Persons with MS
QoL:	Quality of life
SEM:	Standard error of measurement

Dankwoord

Na 8 maanden stage, zit ook de laatste eindspurt, de thesis, erop. Mijn interesse ging uit naar het klinische onderzoek en zo kwam ik terecht bij dit onderwerp, bewegingsanalyse van de bovenste ledematen bij gezonde personen en personen met een neurologische aandoening. Een compleet nieuw terrein, maar juist daarom ook interessant en bijzonder leerzaam! Natuurlijk had ik deze stage en thesis niet kunnen afronden zonder de steun en hulp van een groot aantal mensen die ik graag zou willen bedanken.

Allereerst mijn promotor professor dr. Peter Feys. Dank u wel voor de goede begeleiding en de tijd die u voor mij vrij maakte ondanks de drukke agenda. Ook bedankt voor de kritische vragen, opmerkingen en adviezen die enkel ten goede kwamen aan het onderzoek en de thesis.

Verder mijn dagelijkse begeleidster dra. Ilse Lamers die elke dag voor mij klaarstond, me op weg hielp, oplossingen zocht voor problemen, maar me ook steeds weer motiveerde met haar enthousiasme. Bedankt ook voor het vertrouwen en vrijheid die ik heb gekregen tijdens deze stage.

Geert, die elke keer tijd voor me maakte als er weer eens problemen waren met het meetsysteem of me geduldig doorheen de wereld van hardware en software leidde.

Mijn medestudenten, Elke en Katrijn die ook hun thesis maakten over dit onderzoek. Bedankt voor de hulp en de fijne samenwerking!

Verder natuurlijk ook de proefpersonen. De familieleden en kennissen die minstens twee uur opofferden van hun kostbare tijd om mij verder te helpen met het onderzoek. Heel erg bedankt! Alle proefpersonen uit het Revalidatie en MS-centrum in Overpelt die met hun enthousiasme en humor de testmomenten heel plezierig maakten. En natuurlijk ook Lore die met haar enthousiasme de proefpersonen overhaalde om mee te werken aan dit onderzoek.

Alle andere onderzoekers en medewerkers van REVAL en FOR. Bedankt voor jullie bereidwillige deelname aan de voorbereidende studie, jullie tips, interesse en zeker ook de goede werksfeer!

En tot slot wil ik mijn ouders, zus, familie en vrienden bedanken. Jullie waren een grote steun, niet enkel tijdens de thesis, maar zeker ook al die tijd ervoor. Dank ook aan mijn schoonbroer voor het nalezen van de thesis. Verder wil ik mijn vriend bedanken voor de steun, het luisteren, maar ook voor de ontspannende momenten dit jaar.

Samenvatting

Armdysfunctie is een veel voorkomend gevolg van een neurologische aandoening en heeft een grote invloed op het uitvoeren van activiteiten uit het dagelijks leven. Door middel van kinematica en kinetiek kan er klinische informatie verkregen worden over de beperkingen die deze personen ondervinden, hetgeen nuttig kan zijn in de ontwikkeling van revalidatie therapieën. De meeste studies over bewegingsanalyse hebben zich voornamelijk geconcentreerd op de proximale bewegingen van de armen tijdens het uitvoeren van unilaterale non-functionele taken. Daarom had deze studie tot doel om de distale bewegingen van unilaterale en bilaterale functionele taken te onderzoeken in gezonde en neurologisch aangetaste personen. 15 gezonde personen (45-70 jaar) alsook 6 patiënten (3 multiple sclerose en 3 met een beroerte) namen deel aan deze studie. Met behulp van het meetsysteem CAPTIV-L7000 werd informatie over de uitvoeringstijd, gewrichtshoeken, druk van de duim, wijs- en middelvinger en de duur van de verschillende fasen van een taak verkregen. Twee onderzoeksvragen werden onderzocht. Ten eerste, kan bewegingsanalyse gebruikt worden voor de objectieve evaluatie van de armfunctie tijdens het uitvoeren van functionele taken? De intra-subject variatie in de uitvoering van uni-en bilaterale functionele taken in gezonde en neurologisch aangetaste personen werd gedetermineerd. De resultaten toonden aan dat de uitkomstmaten consistent waren over de drie uitvoeringen in beide groepen behalve voor de druksensoren van de vingers. Er werd wel een grotere variabiliteit voor de uitvoeringstijd en abductie/adductie van de pols in de patiënten waargenomen. Daarnaast werd de test-retest betrouwbaarheid van de evaluatie getest in gezonde personen. Over het algemeen waren de uitkomstmaten betrouwbaar, uitgezonderd de druksensoren. De tweede onderzoeksvraag was, wat zijn de bewegingskenmerken van de functionele taken uitgevoerd in verschillende condities (richtingen, uitvoeringen)? Eerst werd handdominantie onderzocht bij gezonden en een significante invloed op de abductie/adductie van de pols en de druk van de duim werd gevonden. De verschillende condities hadden een invloed op de abductie/adductie van de pols en supinatie/pronatie van de onderarm van de gezonden. Uiteenlopende resultaten werden verkregen voor de sensordata van de patiënten. Echter, voor alle taakcondities werd er een langere uitvoeringstijd geobserveerd voor beide armen van de patiënten. Drie patiënten hadden een langere uitvoeringstijd voor de bimanuele conditie vergeleken met de unilaterale conditie. Mogelijk veroorzaakt door een langere *lift* en *retrieving* fase van respectievelijk de minst en meest aangetaste arm. De bilaterale conditie verlengde de uitvoeringstijd van beide armen van de patiënten door een langere *reaching*, *lift* en *putting down* fase. De *pregrasping* fase werd niet altijd geobserveerd bij de patiënten. Verder werd er aangetoond dat kracht een belangrijke determinant is voor het vermogen om een object te heffen. De verkregen kennis van deze pilootstudie moet worden bevestigd bij meer patiënten.

Abstract

Arm dysfunction is a common consequence of neurological conditions and has a major impact on the performance of activities of daily living (ADL). Kinematic and kinetic analyses can provide clinical information of the deficits these patients have while performing ADL tasks which can be useful in the development of rehabilitation therapies. However, most studies have concentrated on the proximal movements of the arms while executing unilateral non-functional tasks. Therefore, this study aimed to investigate objectively the distal movements of both unilateral and bilateral functional tasks in healthy and neurologically disabled persons. 15 healthy persons (45-70 years) as well as 6 patients (3 multiple sclerosis and 3 stroke) participated in this study. By means of the measuring system CAPTIV-L7000, information about task duration, joint angles, pressure of the thumb, index and middle finger and the duration of the different phases of the tasks were obtained. Two research questions were addressed. First, can movement analysis be used to objectively evaluate upper limb function while executing functional tasks? The intra-subject variation in the performance of uni- and bilateral functional tasks in healthy and neurologically disabled subjects was determined. The results showed that the outcome measures were consistent over the three performances in both groups except for the pressure sensors of the fingers. However, patients showed more variability for task duration and wrist abduction/adduction. In addition, the test-retest reliability of the evaluation was tested in healthy subjects. In general, all the outcome parameters showed to be reliable, except for the pressure sensors. The second research question was, what are the movement characteristics used to perform functional tasks in different conditions (directions and modalities)? First, hand dominance was investigated in healthy subjects and it was shown that it had mainly a significant influence on wrist abduction/adduction and the pressure of the thumb. The conditions had an influence on wrist abduction/adduction and forearm supination/pronation in the healthy subjects. Highly diverse results were obtained for the sensor data of the patients. However, for all the task conditions, a longer task duration was observed for both hands of the patients. Three patients showed a longer task duration for the bimanual execution compared to the unilateral execution. This execution may have prolonged the execution of the less and more impaired arm mainly by an increase of the lift and retrieving phase respectively. Bilateral execution resulted for both hands of the patients in an increased task duration because of a longer reaching, lift and putting down phase. Pregrasping phase was not always observed in the patients. Furthermore, it was shown that strength was the mean determinant of the ability to lift an object. In the future, the acquired knowledge of this baseline pilot study needs to be verified in more patients.

1 Introduction

First, the background of the neurological conditions multiple sclerosis (MS) and stroke and one of their consequences, upper limb dysfunction will be discussed. Then, the main rehabilitation methods and clinical measurements used to train and evaluate the upper limb function will be given. Last, the use of kinematic and kinetic in the evaluation of the upper limb function will be discussed.

1.1 Neurological conditions

Neurological conditions such as stroke and MS are common and have a high disease burden. These conditions are caused by structural and functional disorders of the brain and spinal cord and are characterized by a broad spectrum of disorders throughout the body and different neurological systems.

1.1.1 Multiple sclerosis

MS is a chronic inflammatory demyelinating disease of the central nervous system (CNS) with a prevalence of 1 per 1000 population [1]. It typically affects young adults between the age of 20 and 45 and can be present in different forms [2]. The cause of this disease remains to be elucidated. A hypothesis is that auto-immune cells in a genetically susceptible subject are activated and attack the myelin around the axons, which eventually leads to axon degeneration [3]. As a consequence, nerve signals are not well conducted and this leads to a variety of symptoms for instance visual, cognitive, bladder and bowel deficits but also loss of strength, sensation, coordination, balance and occurrence of spasticity. Because the plaques are mostly spread throughout the CNS, a variety of symptoms can occur at two sides of the body [4]. In the early stage of the disease, most of the persons with MS (PwMS) suffer from gait impairment. In a later stage, upper limb dysfunction become apparent.

1.1.2 Stroke

In contrast to MS, which presumably affects young adults, the mean age of people having a stroke or cerebrovascular accident (CVA) is 70.7 year [5]. Worldwide, the prevalence is between 5 and 10 per 1000 population [6]. It is the leading cause of disability in elderly in Europe and America [7, 8]. Stroke is mostly caused by ischemia and to a lesser extent by hemorrhage of a blood vessel in the brain. Depending on the affected area of the brain, various symptoms, comparable to those seen in PwMS, can occur contralateral to the brain lesion [9]. Unfortunately, at three months post stroke, only 20% of the patients regain their normal function [10].

1.2 Upper limb dysfunction

An important consequence of neurological disorders is upper limb dysfunction [11]. It has been reported for 77.4 % of stroke patients [12]. In a later phase, at least 66% of PwMS will face upper limb dysfunction [13]. It has a major impact on the quality of life (QoL) and functional independence, because the precise coordination between both hands and arms is required to accomplish many activities of daily living (ADL) such as eating, typing, dressing, personal hygiene, etc. Half of the PwMS are restricted in performing ADL tasks and a third report that it influences their social life [13]. One year after stroke, it was determined that upper limb dysfunction had still a detrimental impact on self-care, usual activities, pain/discomfort and anxiety/depression. Therefore, upper limb dysfunction has a major influence on the perceived QoL [14]. These results show that it is important that the hemiparetic arm(s) will be reintegrated in the execution of ADL.

1.3 Rehabilitation of the upper limbs by exercise interventions

Both unilateral and bilateral training interventions have been suggested to improve the arm function of PwMS and stroke patients. However, it is still not clear which of these interventions is preferred for rehabilitation and to which degree improvements are clinical meaningful.

1.3.1 Unilateral arm training

In research, a lot of attention has gone to the rehabilitation of the upper limb by constraint-induced movement therapy (CIMT) and robot-aided therapy. In daily life, many patients use their less impaired arm to perform ADL. The purpose of CIMT is to overcome the non-use of their hemiparetic arm and stimulate the reintegration of this arm in the execution of ADL. This is accomplished by restraining the less impaired arm for most waking hours during 2 weeks or longer. In addition, the patients will train their hemiparetic arm by executing repetitive tasks during the same time period [15]. Robot-aided therapy aims to regain the patient's normal arm function. The robot is often used in combination with a virtual environment which gives visual and haptic feedback while performing the tasks. Besides, the robot can support the arm during execution which make it, in contrast to CIMT, useful for patients with severe arm dysfunction [16].

In stroke, these therapies have been well investigated and showed beneficial results. Wolf et al. showed in a group of 222 stroke patients that CIMT leads to a larger gain of the upper limb function after a two week intervention than the conventional therapy [17]. A robotic therapy in 42 persons with one-year post stroke demonstrated significant improvements in motor impairment, wrist and elbow movements, muscle strength and a reduction of shoulder pain [18].

Despite the observations that these therapies have beneficial effects in stroke patients and that upper limb dysfunction has a major impact on the execution of ADL, not many of these therapies have been attempted in PwMS. Most studies in PwMS concentrated on the lower limbs and therefore the rehabilitation potential of the upper limbs of PwMS was unknown. However, recently, pilot studies have been published which show positive effects on the arm function of PwMS. A study by Mark et al. published preliminary data which suggested that CIMT improved the functional ability and reported increased upper extremity use after therapy in 5 persons with progressive MS [15]. Vergaro et al. investigated the effect of robot-aided therapy in a limited study sample of 8 PwMS. They found an improvement in movement smoothness and coordination [19]. Similar findings were reported by Carpinella et al. [20]. Gijbels et al. showed functional improvement of the upper limb function in 9 high-level disabled PwMS after an 8 week robotic therapy [21].

1.3.2 Bilateral arm training

Robot-aided therapy and constraint-induced interventions mainly focus on unilateral rehabilitation while both upper extremities are necessary to accomplish many ADL. In addition, during CIMT, many of these patients will perform during the waking hours ADL, that are normally performed by two arms, in a compensatory manner with their hemiparetic arm. These compensations, which has been suggested to be long-term, are mostly inefficient and it will take more time to accomplish the tasks with one hand. Therefore, it seems reasonable to do interventions which aims to improve the upper extremity function by training both arms. An example of such therapy is bilateral isokinematic training (BIT) which comprise spatiotemporally bilateral identical movements that are performed with each limb independently. It was shown that this therapy improved the movement pattern of the performances in stroke patients [22]. Hesse et al. compared the effect of a bilateral computerized arm trainer (AT) and electromyography-initiated electrical stimulation (ES) of the paretic wrist extensor in 44 severely affected subacute stroke patients. Training every workday for 6 weeks resulted in significant better scores for upper limb motor power and function in the AT group compared with the ES group [23].

1.3.3 Comparison unilateral and bilateral arm training

The results of bilateral training interventions are mixed. Some studies show a benefit of bilateral training compared to unilateral training, while others show the opposite. Summers et al. stated that bilateral training resulted in a greater reduction in movement time of the impaired limb and higher improvement in upper limb function compared to the subjects who received unilateral training [24]. However, Morris et al. could not show that bilateral training was more efficient compared to unilateral training in acute stroke patients. Moreover, bilateral training seemed to be less beneficial for the recovery of dexterity [25].

1.4 Evaluation of the upper limb function

Clinical tests and patient-reported outcome measures for arm function can be categorized following the International Classification of Functioning, Disability and Health (ICF). It describes and measures health and disability of a person on three levels namely function, activity and participation [26]. For instance, the motricity index (MI) which determines the muscle weakness in impaired patients, is a test on function level. Commonly used tests such as the nine hole peg test (9HPT), pegboard test, action research arm test (ARAT) and Box and Block test evaluate the upper limb on activity level [27-29]. These clinical measurements show some limitations. First of all, these tests only access the upper limb unilaterally while most of the ADL are executed bilaterally. Besides, some of these tests are not sensitive enough to determine small and specific changes in the upper limb function and the subjectivity of some tests cannot be ignored [30]. Furthermore, the functional use of the arm in daily life is assessed by means of self-reported questionnaires, for example the motor activity log (MAL). This questionnaire consists of 30 ADL tasks such as open a drawer, pick up the phone, put on socks etc. The subjects are asked to rate how well and how much they use their hemiparetic arm to accomplish these tasks at a six point scale [31]. Another questionnaire, which addresses bimanual tasks is the ABILHAND. This questionnaire consists of 23 ADL which are all bilaterally. The subjects have to indicate whether the task is impossible, with some difficulty or ease [32]. To test on participation level, questionnaires as for instance the Impact on Participation and Autonomy (IPA) are used. Aspects that are assessed are for example social relationships, family, financial independence,.. [33]. It is remarkable that improvements in the execution of the clinical tests such as the ARAT are often not reflected in the functional use of the upper limbs in daily life when assessed by the MAL. An explanation could be that these clinical tests do not measure relevant parameters or that the patients have learned to use their less impaired arm to perform the ADL tasks despite the ability of the hemiparetic arm to perform these tasks [34].

1.5 Kinematics and kinetics

The above limitations point out the need for objective evaluation of both unilateral and bilateral movements in daily life. In this aspect, kinematics and kinetics can be interesting tools in objectifying the evaluation. In addition, as interventions suggest that the upper limbs have rehabilitation potential, it is interesting to investigate the movements of the upper limbs more in detail both for developing accurate assessment methods as well as providing guidelines towards therapy. For this purpose, kinematics and kinetics can also be used. Kinematics describes body movements in time and space by giving information about the joint angle, velocity and accelerations whereas kinetics describes the underlying forces, powers and energies that enable the person to make movements [11, 35]. Movement analysis of the lower limbs is thoroughly investigated in persons with stroke and MS and in children with cerebral palsy (CP). Nowadays, it is used as an evaluation tool mainly in children with CP and stroke patients. However, movement analysis of the upper limbs is still a challenging task. Unlike the lower limb, a large variation of movements are possible with the upper limb given the possibility to manipulate various objects in different manners. In addition, the arm consists of multiple joints which results in complex interactions. Moreover, there is no single simple activity of daily life that requires the execution of all the movements [36].

1.5.1 Kinetics of the impaired hand

As many daily life tasks require the fine manipulation of objects, it is important to understand more about the interaction of the fingers and the forces that are generated while handling an object. A study investigated the effects of stroke on fingertip force. It was determined that the fingers of the impaired arm, compared to the unimpaired arm, generated 36% less peak force. Besides, in healthy subjects, it is observed that the peak force produced by a finger in a multi-finger task is smaller than its peak force in a similar single-finger task (force deficit defect). In stroke patients, the peak force in a multi-finger task was less decreased compared to healthy subjects. In contrast, the enslaving effect, i.e. the involuntary force generation of other fingers during voluntary force generation of 1 finger, was increased. Both these findings could be explained by a high involvement of the index finger and middle finger in force generation in stroke patients. Unexpected, bimanual deficit, which is the observation that the generated force during bimanual tasks is lower than during unilateral tasks in healthy persons, was observed to the same extent in stroke patients. This may suggest that interhemispheric interactions are preserved in these patients [37]. In another study handling about force control in stroke patients, it was showed that after the maximum grip force during lifting of an object with the impaired hand, the force further increased while the opposite occurred when the object was lifted with the unimpaired hand Moreover, the impaired hand generated a higher grip force while lifting, holding and moving the object compared to the unimpaired hand The average ratio between maximum grip and load forces produced by the impaired hand of the stroke patients was approximately 100% higher than the healthy controls. This suggests a deficit in scaling of the grip force by stroke patients [38].

1.5.2 Effect of movement direction on the kinematics of unilateral tasks

Early in the recovery of stroke, spasticity and movement synergies become apparent. Movement synergies are defined as stereotypic movement patterns of the entire limb that reflect loss of independent joint control. As a result, it can be suggested that some movement directions will be more difficult to execute compared to others [39]. Cirstea et al. showed difficulties in pointing to contralateral located targets. It was suggested that crossing the body midline is more difficult because a complex coordination of elbow extension with shoulder flexion and horizontal adduction is needed [40]. A study by Messier et al. observed the upper limb while displacing a cone 45° outwards, inwards and forwards. They found more trunk flexion in the 45° directions. No significant different degrees in elbow extension and shoulder abduction were observed for the three directions [41]. Another study in which subjects had to reach towards a screen, showed that reaching up and across the body were the movements associated with the largest decrease in active range of motion. Also, the speed to higher targets decreased by 12%. No effect of target location was observed for movement smoothness, straightness and direction [42]. Levin et al. observed in stroke patients that movements to the contralateral and far targets produced less smooth movements, larger variability of movement trajectories and decrease in interjoint coordination in comparison to the ipsilateral targets. Moreover, the movement distances and joint excursions were decreased for the contralateral and far targets in the affected compared with the non-affected arm. These results show that movement disruption is rather due to a disruption of interjoint coordination between elbow and shoulder than movement synergies, because movement made out of the synergy pattern (ipsilateral object) showed no more disruption to movements made in the synergy pattern (contralateral object) [43].

1.5.3 Kinematics and kinetics of bilateral tasks

As studies investigating the rehabilitation potential of bilateral training interventions could not come to a consensus, it is important to learn more about how the upper limbs move during these movements. Studies about movement analysis have mainly focused on the movement characteristics of unilateral tasks, therefore not much is known about the characteristics of bilateral tasks. In neurologically disabled persons, bilateral movements may improve the performance of the more paretic limb. A study of McCombe et al. examined the movement time and peak velocity of the upper limbs in 16 stroke patients in sequential and simultaneous bilateral functional reaching tasks. Results showed that the paretic and non-paretic limb were temporally coupled. Furthermore, the movement time of the paretic limb was slower when first the non-paretic limb and then the paretic limb reached sequentially compared to the simultaneous movement [44].

However, in convenience with bilateral training interventions, other studies show a detrimental effect for the less impaired arm and no effect for the more impaired upper limb. Messier et al. compared the movement characteristics of unilateral and parallel bilateral tasks in 13 healthy persons and 15 stroke patients. It was showed that more trunk flexion, less elbow extension and shoulder abduction was observed during bilateral task execution compared to the unilateral task by both groups. However in the unilateral task, elbow extension of the non-paretic limb did not differ with that of the control subjects. This suggests that the non-paretic limb adjust its performance to the paretic limb [41]. A study investigated in 7 children with hemiplegic CP fingertip force control while unimanual and bimanual lifting an object. Unimanual lifting with the more impaired hand was significant longer than with the less impaired hand. However, it was shown that bimanual lifting equaled the movement duration of the task. Bimanual lifting slowed down the less impaired hand by an increase in duration of the load, transport and release phase. The same was observed for grip force [45].

1.5.4 Kinematics of functional tasks

Most of the studies on kinematics of the upper limbs have concentrated on the analysis of proximal arm joints during unilateral non-functional tasks such as pointing and reaching. For instance, Kamper et al. investigated the quality of reaching of the paretic arm of stroke patients. It was reported that chronic stroke patients have a reduced range, speed and smoothness of movements, and more movement direction noise while reaching compared to their non-paretic arm or healthy controls [42].

However, studies have shown that the kinematics of the upper extremity depends on the goal of the tasks. In order words, reaching to an object or also grasping it results in different movement characteristics [46]. Therefore, there is growing interest to the movement characteristics of more functional tasks. However, in these studies, the subjects had to perform mostly unilateral tasks such as bringing the hand to the mouth, touching contralateral axilla, combing hair and drinking with a glass. Additionally, studies analyzing movement patterns of the upper limb have mainly focused on the proximal part of the upper limb. i.e. the shoulder and elbow. However, also the distal part namely the forearm and the hand are of major importance in the execution of ADL. Moreover, a study in patients with spinal cord injury reported that the greatest differences between the patients and the control group were observed in the wrist [46]. In addition, in hemiparetic subjects, the largest decrease in range of motion was observed in the wrist [47]. Besides, movement analysis of functional tasks in patients with upper limb dysfunction is not well investigated. Recently, a study about the kinematics of a drinking task in 19 stroke patients have been published. They observed significant larger movement times, less smooth movements, less elbow extension, more shoulder abduction and trunk involvement compared to the healthy subjects [30] Another study in 14 left hemiparetic stroke patients showed a longer movement time, less smoothly and lower peak velocity to reach and transport a jar. However, no significant differences in grasping kinematics were found [48]. Besides, to our knowledge, kinematic analyses of functional upper limb movements in PwMS have not been studied before.

1.6 Study aim

Movement analysis of functional tasks in neurologically impaired persons is not well investigated. In addition, kinematic studies mostly focus on unilateral non-functional tasks and mainly observe the performance of the proximal part of the upper limbs. Therefore, this study aims to analyze the distal movements of healthy and neurologically impaired (MS and stroke) persons while executing both unilateral and bilateral tasks. The following research questions will be postulated. First, can movement analysis be used to objectively evaluate upper limb function while executing functional tasks? Second, what are the movement characteristics used to perform functional tasks in different conditions? In order to find an answer to these questions, both uni- and bilateral functional tasks will be executed by healthy persons and a small group of PwMS and stroke patients (age between 45-70 years). Their movements will be analyzed by integrating data from sensors and video recordings. We expect that the kinetics and kinematics of more functional uni- and bilateral movements can be used to objectively evaluate the distal arm function in healthy and neurological disabled persons and to identify its movement characteristics. To investigate the first research question, the consistency or intra-subject variation in the performance of uni- and bilateral functional tasks in healthy and neurologically disabled subjects will be examined. In addition, the test-retest intra-rater reliability of applying the sensors and thus quantifying the performance in healthy subjects will be tested. For the second research question, the influence of hand dominance, movement direction and the performance of a task by one or two hands on the movement characteristics will be examined and this data will be compared with descriptive data of PwMS and stroke patients.

This study makes use of a portable and an user-friendly measuring system. The results of this study will clarify the potential of this system to objectively describe movement characteristics. Furthermore, the movement characteristics of functional tasks will be explored in healthy and neurologically disabled persons. The acquired knowledge about the strength, joint angle and task duration used to perform a particular movement and the observed differences between patients and healthy subjects can provide a first indication about the deficits of patients in executing the tasks. In the future, more in depth research on these findings can be done with more advanced movement analysis systems like three-dimensional analysis.

2 Patients and methods

2.1 Participants

Healthy and neurologically impaired persons between the age of 45 and 70 years participated in this study. 15 healthy subjects of which 8 women and 7 men (mean age 55.2 years, SD 7.35 years) were involved in this study. The patient group was recruited from the Rehabilitation and MS centre Overpelt and consisted of 3 PwMS and 3 stroke patients (table 1). Background and clinical information of these patients is given in table 2 except for CVA patient 2 due to practical issues. Inclusion criteria were diagnosis of MS (Mc Donald criteria) or a clinical definite diagnosis of Stroke (supratentorial) with at least 3 months post-stroke and upper limb dysfunction due to paresis (MI < 85/100). Patients were excluded when they had complete loss of arm function due to severe muscle weakness or severe spasticity (MI < 20, Modified Asworth Scale score > 9) and had a relapse or taken a relapse-related medical treatment with glucocorticoids in the last month prior to the measurements. Both healthy persons and patients were excluded from the study when they had surgery of the upper limb, severe cognitive or visual deficits, neglect, apraxia or any other diagnosis (e.g. neurological, orthopaedic, rheumatism,...) that could have an influence on the arm function.

Hand dominance was determined by the Edinburgh inventory (Oldfield 1971), a questionnaire which consists of 20 ADL tasks [49]. The subjects were asked to fill in their hand preference for each item. The laterality quotient (LQ) was calculated for each subject with the following formula: $LQ = \frac{(\text{sum right hand}) - (\text{sum left hand})}{(\text{sum right+left hand})} * 100$. Subjects were determined as right-handed when LQ was above 60, left- handed when LQ was below -60 and ambidextrous when the score was between -60 and 60 [50]. Only right-handed persons were included in this study.

The study was approved by the ethics commission of the university of Hasselt and that of the Rehabilitation and MS centre Overpelt. All subjects gave written informed consent after receiving written and oral information about the study.

Table 1. Demographic data of healthy subjects (n=15), PwMS (MS 1-3) and stroke patients (CVA 1-3).

	gender	age	hand dominance
Healthy	7M/8F	55,2 ± 7,35 (47-69)	right
MS 1	M	55	right
MS 2	M	61	right
MS 3	M	56	right
CVA 1	M	53	right
CVA 2	M	52	right
CVA 3	M	68	right

M, male; F, female.

Table 2. Background and clinical information of MS (1-3) and CVA (1-3) patients.

		MS 1	MS 2	MS 3		CVA 1	CVA 2	CVA 3
type MS		SP	SP	SP	**type of CVA**	-	ischemic	-
EDSS		6	8	8,5	**month afther diagnosis**	10	3	36
most impaired side		left	left	left	**hemiplegic side**	right	left	left
ARAT	**R**	43	38	57		56	-	57
	L	42	38	43		57	-	39
ARAT 5-finger grip	**R**	16	12	18		18	-	18
	L	15	12	18		18	-	12
9HPT (s)	**R**	251	53	55		51	-	31
	L	202	51	NM		36	-	52
motricity index	**R**	66	91	76		76	-	100
	L	66	70	66		99	-	76
Modified Ashworth Scale	**R**	1	0	0		1	-	0
	L	1	0	0		0	-	1
JAMAR dynamometer (kg)	**R**	10,6	14,6	28,4		38	-	47,4
	L	6,6	15,1	19,4		36,45	-	32,2
key grip (kg)	**R**	2,2	5,4	2,3		6	-	11,3
	L	2,1	5,3	3,3		8,6	-	9,8
three Jaw grip (kg)	**R**	1,8	3,9	1,3		11,2	-	6,9
	L	1,7	4	0		8,4	-	2,5
tip to tip grip (kg)	**R**	1	2,9	2,1		6,7	-	4,8
	L	1	3,8	0,8		6,4	-	3,2

EDSS, Expanded Disability Status Scale; SP, secondary progressive MS; R, right; L, left; ARAT, action research arm test; 9HPT, nine hole peg test.

2.2 Instrumentation and outcome measures

The movements were analyzed by the measurement device CAPTIV-L7000 (TEA, France) which is a portable system that integrates data derived of goniometers (SG65 by Biometrics Ltd Gwent, UK), torsiometers (Q110 and Q150 by Biometrics Ltd Gwent, UK) and pressure sensors with video images. It has an accuracy of 2° and data was sampled at 32 Hz. Goniometer and torsiometer provided position information (degrees°) of respectively the wrist (abduction, adduction, flexion and extension) and the forearm (supination and pronation). The distal part of the goniometer was placed 1.5 cm of caput methacarpale III and the proximal part was placed in line with it. The distal part of the torsiometer was attached ventro-medial, near the palmaris longus. In respect to the distal part, the proximal part was placed with an angle of 90° ventro-medial on the muscle flexor of the hand. These sensors were placed in such way that the position in the anatomical position of the joint corresponded to zero. The interpretation of the sign of the outcome measure refers to a specific movement. For the right hand, positive values of these sensors were defined as adduction, flexion and supination. For the left hand, this was respectively abduction, flexion and pronation. Negative values are the opposite outcome measures. Besides, the pressure of the thumb, index finger and middle finger (kg/cm^2) were derived by pressure sensors. These were attached with tape (Micropore™ Surgical Tape, U.S.) on the ventral distal interphalangeal joint of the thumb, index finger and middle finger. Sensors were fixed to the skin using double sided anti-allergic adhesive tape (Samcon, Merelbeke, Belgium).

2.3 Experimental tasks

2 movement tasks, lifting and transporting an object, with different conditions were executed by the subjects (Table 3). To investigate the influence of movement direction on the movement characteristics (DIR), the subjects had to transport or lift a wooden block (7.5 cm^3, 196 g) separately with the left and right hand to the end position in three different directions i.e. forward, outward and inward. Then, they were instructed to lay their hands back in start position and to transport or lift the block back to the start position. Start position of the block was at shoulder width (figure 1). The influence of executing a task with one or two hands (EXE) was determined by lifting the wooden block forwards to the end position with the right and the left hand separately, bimanual and lifting two blocks simultaneously with two hands (bilateral). After bringing the hands back in start position, the blocks were put down back by the subjects on the start position, in front of the sternum (figure 1). Besides, subjects had to transport the same block from shoulder width inwards to the end position with each hand separately and bilaterally and go back to start position. Next, the block(s) were transported to the start position. Bimanual execution of the transporting tasks was not possible. These tasks were selected because they require a broad range of movements and the tasks lifting an object is already used in clinical tests such as the ARAT. All the tasks were executed with a standardized handgrip. In this way, differences in joint angles or pressure between and within the subjects due to a different handgrip was kept to a minimum. A preparatory study in 20 healthy subjects was performed to determine the most preferred handgrip for each task.

Table 3. Description of the tasks, executed in different conditions and the used handgrip.

	task	**task condition**	**handgrip**
influence of movement direction (DIR)	lift an object unilateral	inward forward outward	
	transport an object unilateral	inward forward outward	
influence of execution by one or two hand (EXE)	lift an object foward	unilateral bimanual bilateral	
	transport an object inward	unilateral bilateral	

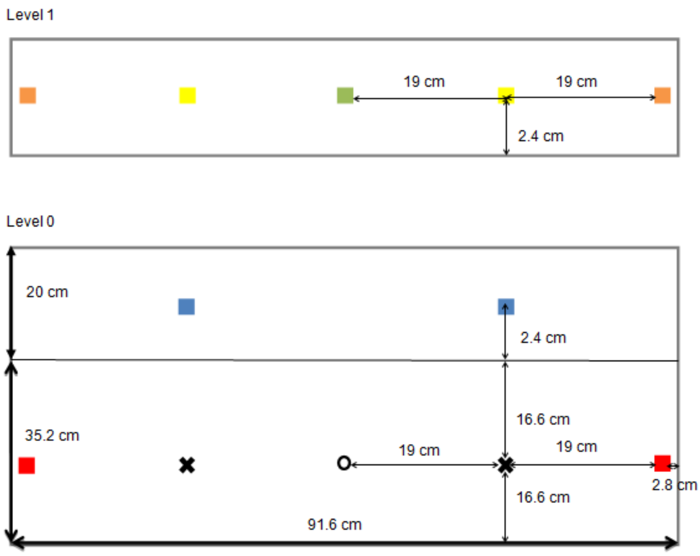

Figure 1. Start and end positions of the tasks. Level 0 was the height of the table. Level 1 was 37.5 cm higher than level 0 (same height as ARAT). The distances are given on the figure and are equal for the left side. Movement directions were indicated by colored marks: outward (red and orange quadrilateral), inward (circle and green quadrilateral) and forward (blue and yellow quadrilateral). Start position at shoulder width are the crosses, while the start position in front of the sternum is marked by a circle.

These tasks were broken down in phases to determine differences in duration between healthy controls and neurologically disabled persons. The transporting tasks were divided in the following phases: reaching, pregrasping, grasping, transporting away, release, retrieving and transporting return. Lifting tasks were separated in reaching, pregrasping, grasping, lifting, release, retrieving and put down. Description and the order of the different phases are given in figure 2 and table 4. Start and end of the phases were determined by observing the video images in the CAPTIV software at very low speed.

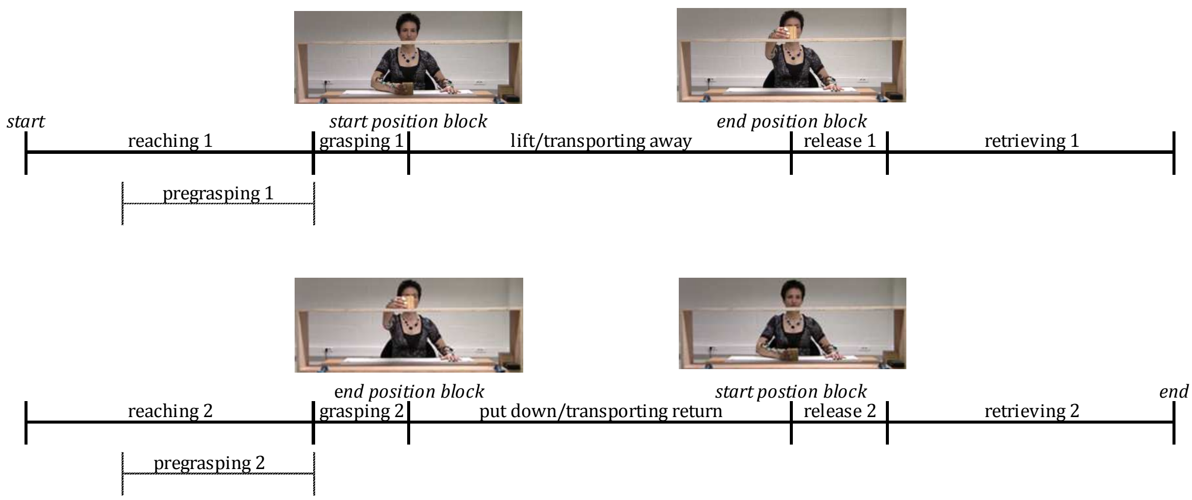

Figure 2. Phases of the tasks, lift and transport an object. First, the block had to be transported/lifted from start position to end position. Subjects returned to start position. Then, the block had to be transported/put down from end position back to the start position.

Table 4. Description of the phases of the tasks.

phase	start	end
reaching 1,2	hand moves towards object	shoulder and elbow are stabilized, hand starts closing to grasp object
pregrasping 1,2	hand in grasp posture	start of grasping
grasping 1,2	shoulder and elbow are stabilized, hand closes to grasp object	object is displaced to start/end position
transporting away	object is displaced to end position	object is placed at end position
lift	object is lifted up to place at end position	object is placed at end position
release 1,2	object is placed at start/end position	hand is open, no contact with object, arm goes back to start position
retrieving 1,2	hand is open, no contact with object, arm goes back to start position	hand in start position
transporting return	object is displaced to start position	object is placed at start position
put down	object is taken up to put down on start position	objects is placed at start position

1, phases of the first part of the task (transporting away or lifting object from start position to end position); 2, phases of second part of the task (transporting return or putting down object from end position to start position)

2.4 Experimental set up and procedure

Subjects were seated in a standardized position on an straight-back chair or in a wheelchair with their trunk against the back of the chair. They were positioned in such a way that their sternum corresponded to the middle of the experimental set up, feet rest on the floor with the knee flexed in 90°, the upper limb was placed against the trunk with elbow position 90° flexed and supported on the table (figure 3 a and b). Subjects were instructed to lay their hands in pronation. An adjustable table was used to make sure that the subjects could sit in the correct position. Subjects-table distance was determined by extending the subjects arm. When their fingertips touched the backside of the shelf of level 1 (figure 3 a), the subjects were in the right position. 2 video cameras (Canon LEGRIA HFR16, 25Hz) were placed in such a way that they visualized the front and side view of the patient his chest. The objects were placed at marked sites of 2 cm^2. The tasks, lifting and transporting an object were executed with wooden blocks derived from the ARAT.

Figure 3. Start position of subjects **a.** front view. **b.** side view.

Before the performances, standardized and well-defined oral and visual instructions about the execution of the tasks were given. Subjects were instructed to practice each task twice to get used of the tasks. To investigate the effect of movement direction and the effect of unilateral, bilateral and bimanual execution of the tasks, the subjects performed the tasks in a randomized order with both the right and the left hand at self-selected speed. To minimize the effect of fatigue, 2 minutes break were given between the tasks. All the tasks were executed 5 times. The middle three performances were taken for analysis [30].

The reliability of evaluation was determined in healthy subjects. After the first test session, the sensors were removed and 15 minutes break were given. Afterwards, the sensors were replaced by the same instructor and one condition of each task was repeated. The outward and forward direction were repeated for transport and lift an object respectively. In addition, the unilateral condition of the lift and transport tasks were repeated. All the tasks were also this time executed with the right and the left hand.

2.5 Statistical analysis

The statistics were done with the statistical program SPSS. Significance was set at the 0.05 probability level. To investigate the intra-subject variation in execution of the tasks, the intraclass correlation (ICC; 2,1) of the outcome measures of the three middle performances was calculated [51]. This was calculated for each task and separately for the patient and control group. The consistency of the parameters of the retest was not calculated, because it was assumed that this was comparable to the consistency of the parameters of the first test session. ICC was defined as excellent when it was higher than 0.90, good between 0.75-0.90, moderate between 0.50-0.74 and poor when it was below 0.50 [45]. Since, the subject number was limited, the reliability of the ICC's could be reduced. Therefore, also Spearman correlations were calculated and these results were compared with the ICC's. Comparable results were obtained, so only the results of the ICC's are shown. The test-retest intra-rater reliability was determined by an ICC model (2,3) [51]. The correlations between the mean of the three middle performances of the test and retest were calculated. Also Spearman correlations and Bland-Altman plots were made to visualize the agreement of the parameters of the test and retest. Outliers were excluded for ICC calculation. The standard error of measurement (SEM) was estimated as the square root of the mean square error term from the analysis of variance (ANOVA) [51]. For the research question in which the influence of hand dominance, movement direction and the performance of a task by one or two hands on the movement characteristics was investigated, only data from the healthy subjects were statistically analyzed because of a too limited number of patients in the CVA and MS group. To determine the influence of hand dominance on the movement characteristics, a Wilcoxon signed-rank test was used. The influence of directions and the performance of a task by one hand or two hands was examined by means of a Friedman test. Wilcoxon signed-rank test with Bonferroni correction ($p < 0.017$) was used as post-hoc test. The tasks transport an object forwards which was executed unilateral and bilateral was compared with a Wilcoxon signed-rank test. Correlations between the clinical measures and the tasks were investigated by means of Spearman correlations.

3 Results

In order to assess the reliability of the measuring system and the evaluation, intra-subject variation and intra-rater reliability by means of ICC was investigated. In addition, movement characteristics for the tasks were determined and the influence of hand dominance, executing a task in different directions and with one or two hand was examined in healthy persons. Furthermore, some descriptive data of the movement characteristics of patient cases are presented and compared with the control group.

3.1 Intra-subject variation

Subjects had to perform the movement tasks 5 times with both their right and left hand. The three middle performances were taken for statistical analysis. It was investigated whether the subjects executed the tasks 3 times in the same manner. For both the healthy and patient group, the ICC was calculated from the mean of the task duration, joint angles and the maximum pressure measured during each execution. ICC from the mean pressure during execution could not be calculated due to very low values. Results are presented for the right and left hand for each task condition (table 5).

The healthy subject group showed very high ICC's for the outcome measures task duration, wrist flexion/extension, wrist abduction/adduction and forearm supination/pronation for both hands. All the ICC's were above 0.90 which can be interpreted as a very high consistency for these parameters. For the tasks executed in different directions, the pressure of the thumb showed for the right hand good to excellent correlations and for the left hand good correlations. The same was observed for the tasks with different execution conditions, although all the correlations were slightly lower, ranging from moderate to good. The consistency of the pressure of the index and middle finger was very variable for both hands. Correlations ranging from poor to excellent were obtained.

In general, the results of the intra-subject variation of the patient group showed a moderate to excellent correlation for most of the parameters (table 6). Task duration showed a good to excellent correlation. Only for some of the tasks executed in different directions, in particular, transporting forwards with the right hand and lift outward with the left hand, a moderate ICC was obtained. For the tasks executed in different execution modes, only lift bilateral showed a moderate ICC for the left hand. Excellent correlations were obtained for the parameters wrist flexion/extension and forearm supination/pronation except for the forearm supination/pronation of the left hand for the task transport an object inwards. The moderate ICC was due to a lower consistency of 1 PwMS for this parameter. Slightly lower correlations were obtained for the outcome measure wrist abduction/adduction.

Table 5. Intra-subject variation for the parameters of the right and left hand during execution of the tasks in healthy subjects (n=15). ICC was calculated from the mean of the task duration, joint angles and the maximum pressure measured during the three executions. Significance was set at 0.05.

					wrist						pressure					
task			task duration		flexion/extension		abduction/adduction		forearm sup/pro		thumb		index finger		middle finger	
			L	R	L	R	L	R	L	R	L	R	L	R	L	R
DIR	lift	forward	0,970**	0,957**	0,968**	0,982**	0,973**	0,971**	0,995**	0,995**	0,802**	0,911**	0,731*	0,353*	0,670**	0,785**
		outward	0,917**	0,969**	0,986**	0,966**	0,987**	0,979**	0,994**	0,994**	0,810**	0,858**	0,692**	0,590**	0,707**	0,930**
		inward	0,962**	0,956**	0,989**	0,948**	0,978**	0,981**	0,995**	0,993**	0,881**	0,914**	0,746**	0,243	0,771**	-0,096
	transport	forward	0,960**	0,982**	0,989**	0,969**	0,977**	0,966**	0,997**	0,995**	0,741**	0,913**	0,759**	0,616**	0,346*	0,661**
		outward	0,953**	0,958**	0,987**	0,967**	0,976**	0,948**	0,995**	0,997**	0,759**	0,901**	0,619**	0,356*	0,872**	0,577**
		inward	0,942**	0,955**	0,977**	0,973**	0,963**	0,949**	0,996**	0,996**	0,749**	0,828**	0,859**	0,643**	0,544**	0,456*
EXE	lift	unilateral	0,912**	0,930**	0,978**	0,986**	0,986**	0,975**	0,995**	0,991**	0,654*	0,790**	0,769**	0,646**	0,850**	0,661**
		bilateral	0,954**	0,959**	0,988**	0,900**	0,988**	0,974**	0,995**	0,995**	0,835**	0,905**	0,402*	0,757**	0,805**	0,778**
		bimanual	0,953**	0,957**	0,989**	0,986**	0,988**	0,975**	0,995**	0,993**	0,576**	0,741**	0,324*	0,490**	0,692**	0,880**
	transport	unilateral	0,957**	0,918**	0,978**	0,946**	0,982**	0,909**	0,995**	0,987**	0,552**	0,860**	0,958**	0,127	0,598**	0,459*
		bilateral	0,918**	0,921**	0,963**	0,974**	0,984**	0,969**	0,992**	0,992**	0,578**	0,738**	0,582**	0,594**	0,909**	-0,037

*p-value < 0,05

**p-value < 0,001

DIR, direction; EXE, execution; L, left; R, right; sup, supination; pro, pronation

Table 6. Intra-subject variation for the parameters of the right and left hand during execution of the tasks in patients (n=6). ICC was calculated from the mean of the task duration, joint angles and the maximum pressure during the three executions. Significance was set at 0,05.

					wrist						pressure					
task			task duration		flexion/extension		abduction/adduction		forearm sup/pro		thumb		indexfinger		middle finger	
			L	R	L	R	L	R	L	R	L	R	L	R	L	R
DIR	lift	forward	0,981**	0,893*	0,924**	0,977**	0,926**	0,960**	0,926**	0,982**	0,842*	0,583*	0,704*	0,775*	0,941**	0,933**
		outward	0,634*	0,86**	0,916**	0,980**	0,752*	0,946**	0,994**	0,986**	0,318	0,873**	0,862**	0,688*	0,786*	0,912**
		inward	0,939**	0,802*	0,932**	0,955**	0,950**	0,919**	0,988**	0,982**	0,500	0,933**	0,500*	0,800*	0,833**	0,963**
	transport	forward	0,955**	0,551*	0,961**	0,921**	0,901**	0,719*	0,995**	0,990**	0,474	0,652*	0,822*	0,688*	0,833*	0,801**
		outward	0,722*	0,941**	0,978**	0,930**	0,851**	0,943**	0,998**	0,992**	0,741*	0,659*	0,865**	0,922**	0,824**	0,803**
		inward	0,926**	0,741*	0,965**	0,919**	0,864**	0,946**	0,682*	0,974**	0,781*	0,263	0,773*	0,605*	0,941**	0,809**
EXE	lift	unilateral	0,959**	0,843*	0,998**	0,964**	0,981**	0,796**	0,998**	0,989**	0,865*	0,822*	-0,171	0,924**	0,468	0,855*
		bilateral	0,551*	0,958**	0,983**	0,987**	0,952**	0,622*	0,998**	0,972**	0,841*	0,937**	0,773*	0,976**	0,408	0,625*
		bimanual	0,752*	0,771*	0,986**	0,992**	0,882**	0,720*	0,986**	0,972**	0,884**	0,892**	0,975**	0,660*	0,794*	0,938**
	transport	unilateral	0,814*	0,952**	0,987**	0,975**	0,942**	0,895**	0,982**	0,970**	0,183	0,865**	0,642*	0,544*	0,917**	0,529*
		bilateral	0,856**	0,851**	0,992**	0,958**	0,951**	0,781**	0,977**	0,993**	0,833**	0,792**	0,943**	0,777*	0,688*	0,786*

*p-value < 0,05

**p-value < 0,001

DIR, direction; EXE, execution; L, left; R, right; sup, supination; pro, pronation

The pressure of the fingers showed, in line with the healthy subjects, very diverse results. Most correlations ranged from moderate to excellent, but also poor correlations were obtained. The consistency of the thumb showed in general better correlations for the tasks with different execution conditions compared to the tasks executed in different directions.

Comparison of the results between the healthy and patient group revealed no remarkable differences. For both groups, high correlations for task duration, forearm pronation/supination, wrist flexion/extension and abduction/adduction were obtained. However, slightly lower correlations for the parameters task duration and wrist abduction/adduction were observed for the patient group. Besides, the pressure of the middle finger showed higher correlations for the tasks executed in different directions compared to the healthy subjects.

3.2 Intra-rater reliability

Intra-rater reliability was determined for the tasks lift and transport an object in the directions forward and outward and in the unilateral execution condition. This was investigated by a test-retest set-up in healthy subjects (n=15). From the mean of the parameters of the three performances from the test and retest, Bland-Altman plots were made to determine outliers. 1 subject was excluded for the parameters wrist abduction/adduction, wrist flexion/extension and forearm supination/pronation. Then, the ICC's and SEM's for both hands were calculated (table 7).

Table 7. Test-retest intra-rater reliability (ICC, SEM) for the outcome measures in healthy subjects (n=15). The mean of task duration and joint angles and the maximum of the pressure were taken to calculate the ICC's. P-value was set at significance level 0,05.

		DIRECTION				EXECUTION			
		lift forward		transport outward		lift unilateral		transport unilateral	
		ICC	SEM	ICC	SEM	ICC	SEM	ICC	SEM
task duration (s)	**R**	0,959**	0,29	0,797**	0,50	0,927**	0,29	0,839**	0,50
	L	0,946**	0,33	0,840*	0,33	0,927*	0,32	0,896**	0,43
wrist abd/add (°)	**R**	0,731*	4,28	0,819*	3,54	0,817*	3,33	0,631*	3,03
	L	0,748*	3,70	0,794*	3,68	0,360	5,67	0,598	4,75
wrist fl/ext (°)	**R**	0,862**	5,16	0,812*	6,37	0,761*	7,03	0,846*	4,73
	L	0,874**	6,40	0,913*	4,54	0,690*	6,93	0,739*	4,78
forearm sup/pro (°)	**R**	0,744*	7,57	0,798*	7,16	0,761*	6,76	0,786*	7,20
	L	0,795*	6,23	0,806*	6,42	0,601*	7,09	0,718*	6,55
pressure thumb	**R**	0,953**	0,11	0,968**	0,12	0,800*	0,11	0,733*	0,09
(kg/cm^2)	**L**	-0,137	0,23	0,479	0,13	0,628*	0,07	0,648*	0,05
pressure index finger	**R**	0,145	0,03	0,886**	0,00	0,538	0,10	0,705	0,11
(kg/cm^2)	**L**	0,530	0,10	0,540	0,08	0,725**	0,13	0,707*	0,13
pressure middle finger	**R**	0,667*	0,03	0,476	0,08	0,697*	0,06	0,449	0,09
(kg/cm^2)	**L**	0,653*	0,09	0,919**	0,08	0,820**	0,15	0,860**	0,08

*p-value < 0,05

**p-value < 0,001

ICC, intraclass correlation; SEM, standard error of measurement; R, right; L, left; abd, abduction; add, adduction; fl, flexion; ext, extension; sup, supination; pro, pronation

3.2.1 Task duration

Task duration showed good reliability for the tasks in which an object was transported and excellent reliability for the tasks in which an object was lifted. The SEM's ranged from 0.29s to 0.50s.

3.2.2 Joint angles

The tasks performed in different directions showed good correlations for wrist abduction/adduction and the SEM's were between 3.54° – 4.28°. This is in contrast to the tasks with different executions conditions which showed rather poor to moderate reliability. In particular, the task lift unilateral had only a correlation of 0.360. However, the SEM's ranged between 3.03° and 5.67°. The ICC's for wrist flexion/extension were good to excellent for the tasks executed in different directions. SEM's ranging between 4.54° to 6.37° were found. Also the tasks with different execution conditions had a good reliability. Only the task lift unilateral with the left hand showed a moderate correlation (0.690) and an estimated SEM of 6.93°. Forearm supination/pronation had a good reliability for the tasks performed in different directions. However, the highest SEM's were obtained (6.23° – 7.57°). A moderate to good reliability was found for the tasks with different execution conditions. SEM's were between 6.55° and 7.20°. Again for the task lift unilateral with the left hand, a lower ICC (0.601) and a SEM of 7.09° was obtained.

3.2.3 Pressure parameters

Excellent reliability for the pressure of the right thumb were obtained for the tasks executed in different directions. Contrary, poor correlations were found for the left thumb. The SEM's ranged between 0.11 kg/cm^2 and 0.23 kg/cm^2. The tasks performed in different execution conditions showed a moderate to good reliability for both hands. Also lower SEM's were obtained (0.05 kg/cm^2 – 0.11 kg/cm^2). Very variable results were obtained for the index and middle finger for the tasks executed in different directions, in particular, poor to excellent correlations were founded. SEM's were between 0.03 kg/cm^2 and 0.10 kg/cm^2. For the tasks performed in different execution conditions, poor to good ICC's were shown. The SEM's ranged between 0.06 kg/cm^2 and 0.15 kg/cm^2. In general, the reliability of the pressure parameters were very variable, therefore, in further analysis, only the pressure of the thumb will be presented to give an indication of the pressure used by healthy subjects and patients. Moreover, the most pressure was measured for this finger in comparison with the other fingers.

3.3 Movement characteristics in healthy subjects and neurologically disabled persons for different directions and execution conditions

In healthy subjects, the effect of hand dominance on the outcome parameters was first examined. Then, it was investigated whether lifting or transporting an object in different directions or execution conditions had an influence on the outcome measures. In addition, descriptive data of the outcome parameters were presented for the patients. Last, the duration of different phases were compared between healthy subjects and patients.

3.3.1 Influence of hand dominance on outcome measures

The influence of hand dominance was investigated to assure that differences in outcome parameters between the most and less impaired arm of the patients were not due to hand dominance. This was determined for all the outcome measures by the Wilcoxon signed-rank test (p-value < 0.05)(table 8).

A significant effect of hand dominance on task duration was only observed for the task transport an object unilateral in which the right hand had a longer task duration than the left hand (table 12). Wrist abduction/adduction was different for the right and left hand for all the tasks. More mean wrist adduction was used by the right hand for the tasks performed in different directions than the left hand. For the tasks performed in different execution conditions, more mean abduction was used by the left hand compared to the right hand (table 9 - 12). The tasks performed in different directions showed significant differences for the pressure of the thumb. Table 9 and 10 show that approximately double pressure was provided by the right thumb compared to the left thumb. Hand dominance had no significant influence on the outcome parameters wrist flexion/extension and forearm supination/pronation.

Table 8. Influence of hand dominance on the outcome measures in healthy subjects (n=15).

task			task duration	wrist abd/add	wrist fl/ext	forearm sup/pro	pressure thumb
DIR	lift	inward	0,86	0,02*	0,85	0,85	<0,01*
		forward	0,42	0,01*	0,73	0,90	0,03*
		outward	0,49	0,02*	0,90	0,68	<0,01*
	transport	inward	0,76	0,05*	0,97	0,86	<0,01*
		forward	0,39	0,05*	0,67	0,87	0,03*
		outward	0,40	0,04	0,68	0,05	<0,01*
EXE	lift	unilateral	1,00	<0,01*	0,60	0,53	0,13
		bimanual	0,29	0,02*	0,32	0,40	1,00
		bilateral	0,13	0,02*	0,45	0,21	0,25
	transport	unilateral	0,05*	<0,01*	0,19	0,26	0,25
		bilateral	0,95	0,05*	0,40	0,07	0,50

Wilcoxon signed-rank test: p-value. *p-value < 0,05.
DIR, direction; EXE, execution; abd, abduction; add, adduction; fl, flexion; ext, extension; sup, supination; pro, pronation

3.3.2 Influence of moving in different directions on outcome measures

It has been suggested that some directions may be more difficult to perform for neurologically impaired patients. Therefore, subjects had to transport and lift an object in three different directions, namely forward, inward and outward. It was investigated whether the outcome parameters differed between the three directions in the healthy subject group by a Friedman test ($p < 0.05$) ($n=15$). Also preliminary data of patients are shown descriptively.

The results of the healthy subjects showed that lifting an object forwards, inwards and outwards had a significant influence on wrist abduction/adduction and forearm supination/pronation on both the right and left hand (table 9). Post-hoc analysis with Wilcoxon signed-rank test ($p < 0.017$) determined that wrist abduction/adduction for the left hand showed a significant difference with the outward direction, whereas the right hand differed significantly between all the directions. The least mean wrist adduction was used by both hands in the outward direction, most in the inward directions. Forearm supination/pronation of the left hand differed between all the directions. For the right hand, a significant difference was founded with the outward direction. Least mean pronation was used in the outward direction. Also the pressure of the right thumb was significantly different between the forward and inward direction with the highest mean pressure for the inward direction. Also interesting, the left thumb used on average half of the pressure of the right thumb.

Data of MS1 could not be obtained, because this person was unable to lift the block. The data showed that in patients the task duration was increased for their both hands for all the tasks with the most impaired hand showing the longest duration. No clear pattern was observed between the directions. MS3 and CVA1 had the most prolonged time for lifting outward with their most impaired arm, while this was the shortest time for patient MS2. Lifting inward had the longest duration for patient CVA2 and 3. A decrease in wrist adduction was observed for the less impaired arm of 4 patients. In addition, CVA1 and CVA2 showed also more abduction for this arm. Less adduction and more abduction was observed for the most impaired arm of 2 patients (MS3 and CVA2). For most patients, lifting inward used most adduction, outward the least which is similar to the healthy subjects. More wrist extension was used by both hands of CVA1 and CVA2. The latter used also more flexion. More extension was also observed for the less impaired arm of MS3. However, less extension was observed for CVA3. In contrast to the healthy subjects, no clear pattern was visible for the directions. More pronation was observed for the most impaired arm of 3 patients. Only for MS3, a decrease of pronation for both arms was observed. The CVA patients demonstrated, like the healthy controls, most pronation for the inward task. The pressure sensors showed no clear difference between the two hands as seen in healthy controls. In general, also less pressure was observed.

Table 9. Mean and range of the outcome measures for the task lift an object executed in the forward (FOR), inward (IN) and outward (OUT) direction. Data is presented for the healthy subjects (mean of 15 subjects), MS (MS 2, 3) and CVA (CVA 1-3) patients for the right and left hand. P-values are given to indicate significant influence of directions on the outcome measures.

Outcome measures			**HEALTHY mean (SD)**		**PATIENTS**									
					MS2		**MS3**		**CVA1**		**CVA2**		**CVA3**	
			L	**R**	**L***	**R**	**L***	**R**	**L**	**R***	**L***	**R**	**L***	**R**
task duration (s)	**FOR**	**mean**	5,85 (1,46)	5,79 (1,29)	13,18	11,74	14,63	7,93	6,38	7,46	9,91	9,52	10,78	9,55
	IN	**mean**	6,08 (1,42)	6,14 (1,43)	12,52	11,67	14,72	7,94	7,60	7,85	11,23	9,86	14,10	10,59
	OUT	**mean**	5,72 (1,27)	5,76 (1,16)	11,56	10,83	29,21	7,44	6,98	7,97	8,81	8,44	11,34	9,66
	p-value		*0,10*	*0,14*										
wrist abd/add (°)	**FOR**	**mean**	-10,07 (6,90)	16,78 (6,50)	-8,00	3,33	5,67	11,67	-1,00	9,33	-1,00	4,00	-5,67	11,33
		range	-21,07; 4,78	1,49; 28,56	-25,00; 8,00	-6,00; 13,67	-7,67; 16,00	3,00; 24,00	-9,67; 11,67	-4,00; 18,00	-12,67; 8,67	-11,33; 17,00	-16,00; 2,00	2,67; 19,67
	IN	**mean**	-11,00 (7,41)	17,98 (7,91)	-6,67	4,33	5,67	14,00	-2,33	10,33	0,67	5,67	-7,00	13,00
		range	-23,16; 5,93	1,44; 30,18	-21,67; 13,00	-6,67; 15,67	-7,33; 17,33	6,33; 28,33	-14,00; 14,33	-6,00; 20,00	-13,00; 10,33	-12,00; 17,33	-18,33; 1,00	1,00; 20,67
	OUT	**mean**	-7,16 (7,03)	13,00 (5,89)	-6,33	1,67	2,00	12,00	2,67	7,33	-1,00	2,67	-3,33	8,00
		range	-19,00; 4,00	0,42; 25,96	-25,67; 6,33	-9,00; 15,67	-9,33; 14,33	0,00; 27,33	-8,00; 15,33	-5,33; 19,00	-11,00; 12,67	-12,67; 17,00	-14,33; 3,67	-3,33; 20,67
	p-value		*<0,01* †‡	*<0,01* §†‡										
wrist fl/ext (°)	**FOR**	**mean**	-22,36 (13,42)	-22,58 (11,48)	-23,00	-25,67	-29,00	-34,67	-42,33	-49,00	-29,00	-25,00	-22,67	-15,33
		range	-47,09; 2,04	-46,07; 1,36	-50,00; 7,67	-52,00; 0,33	-51,67; -5,00	-58,33; -2,33	-61,00; -11,67	-72,00; -1,00	-55,00; 9,00	-61,00; 16,00	-39,33; 6,33	-34,33; 12,33
	IN	**mean**	-22,31 (12,90)	-21,76 (13,55)	-20,33	-25,33	-24,67	-32,33	-41,67	-44,33	-27,67	-28,00	-23,67	-18,33
		range	-46,56; 1,64	-45,89; 1,71	-48,00; 11,67	-51,67; 3,67	-49,00; -6,33	-55,33; -2,67	-58,33; -11,33	-70,67; 2,00	-53,33; 4,00	-67,33; 12,00	-42,00; 5,33	-39,00; 10,67
	OUT	**mean**	-23,22 (11,49)	-24,38 (10,45)	-22,67	-29,67	-25,67	-32,00	-50,00	-50,33	-27,33	-26,00	-22,67	-16,00
		range	-48,38; 2,40	-47,71; -0,13	-50,67; 7,00	-57,00; 1,33	-55,00; -1,67	-56,00; -4,33	-64,33; -14,67	-74,00; -4,33	-57,00; 11,00	-60,67; 16,67	-40,33; 7,00	-39,33; 13,00
	p-value		*0,65*	*0,11*										
forearm sup/pro (°)	**FOR**	**mean**	17,91 (13,09)	-16,60 (11,46)	26,67	-31,00	14,00	-9,67	11,00	-28,67	21,33	-21,33	36,33	-22,33
		range	8,64; 28,27	-27,00; -6,56	15,33; 37,67	-41,67; -23,33	-0,33; 23,33	-18,00; 2,00	3,67; 21,33	-44,33; -15,67	11,00; 31,67	-30,67; -10,00	28,33; 45,00	-29,33; -13,67
	IN	**mean**	19,60 (13,73)	-18,02 (12,39)	25,67	-31,00	13,33	-8,33	14,00	-29,00	22,67	-22,33	37,33	-24,67
		range	9,87; 28,27	-27,53; -7,96	11,67; 36,67	-45,33; -22,33	2,00; 22,33	-16,33; 1,67	8,67; 25,33	-48,00; -13,67	13,33; 31,33	-37,33; -12,33	29,33; 45,33	-30,67; -13,67
	OUT	**mean**	16,40 (12,99)	-14,82 (11,67)	24,33	-32,67	14,00	-6,67	9,33	-26,67	19,33	-19,33	35,00	-23,67
		range	6,07; 28,38	-26,96; -3,73	12,67; 36,33	-48,00; -23,33	0,67; 23,00	-19,67; 4,00	-1,33; 24,33	-45,33; -11,00	7,33; 30,67	-33,00; -6,00	25,00; 45,33	-32,67; -12,67
	p-value		*<0,01* §†‡	*<0,01* †‡										
pressure thumb (kg/cm^2)	**FOR**	**mean**	0,06 (0,05)	0,12 (0,08)	0,00	0,00	0,00	0,00	0,00	0,03	0,10	0,10	0,07	0,10
		max	0,39 (0,23)	0,64 (0,38)	0,13	0,20	0,10	0,17	0,20	0,33	0,30	0,43	0,40	0,40
	IN	**mean**	0,06 (0,05)	0,15 (0,13)	0,00	0,00	0,00	0,00	0,03	0,10	0,10	0,10	0,03	0,10
		max	0,37 (0,21)	0,73 (0,53)	0,10	0,20	0,13	0,13	0,27	0,63	0,37	0,40	0,23	0,40
	OUT	**mean**	0,06 (0,05)	0,13 (0,09)	0,00	0,00	0,00	0,00	0,03	0,20	0,10	0,10	0,07	0,10
		max	0,37 (0,20)	0,66 (0,40)	0,13	0,23	0,13	0,10	0,17	0,73	0,27	0,43	0,27	0,40
	p-value		*0,58*	*0,02* §										

* most impaired hand

Friedman test ($p < 0,05$), post-hoc analysis: Wilcoxon signed-rank test with Bonferroni correction ($p < 0,017$).

§ Significant difference between the directions forward and inward; † Significant difference between the directions forward and outward; ‡ Significant difference between the directions inward and outward

SD, standard deviation; FOR, forward; IN, inward; OUT, outward; L, left; R, right; abd, abduction; add, adduction; fl, flexion; ext, extension; sup, supination; pro, pronation.

The results of transporting an object in different directions showed also differences for the outcome parameters wrist abduction/adduction and forearm supination/pronation (table 10). Wrist abduction/adduction for the left hand differed with the inward direction. A significant difference was observed for the right hand between the directions forward – outward and inward – outward. The inward direction showed for both hands most mean adduction, while the least mean adduction was detected for the outward direction. Forearm supination/pronation differed for the left hand between all the directions, while this parameter differed for the right hand with the inward direction. The highest values were observed in the inward direction.

Like the previous task, the task duration of both hands of the patients was prolonged (table 10). The more impaired hand showed in general a longer duration than the less impaired hand. No clear prolongation for a particular direction was observed among the patients, although there were differences in task duration between the directions within the patients. Half of the patients (MS1, MS2 and CVA2) used more abduction and less adduction compared to the control subjects with their less impaired arm. More abduction and less adduction was observed for MS3 for his most impaired arm. MS2, MS3 and CVA3 used with their less impaired arm the least abduction for the outward direction and most for inward direction, similar to the healthy subjects. However, for the most impaired arm, least adduction was used for the forward direction, most for the inward direction in 4 patients. For the outcome parameter wrist flexion/extension, there were 4 patients who used more extension with their less impaired arm. CVA1 and CVA2 used also more extension with their most impaired arm. The latter subject showed also more flexion. MS1 and CVA3, on the other hand, used less extension for the most and less impaired hand respectively. More flexion was observed for 2 patients their most impaired hand. For the less impaired arm, most extension was observed for 3 patients in the forward direction which is in convenience with the healthy subjects. For the most impaired arm, most extension was visible by 4 patients for the inward direction. 4 patients used more pronation for their most impaired arm. In general, the highest pronation was observed for transporting an object inwards. This is in line with the results of the healthy subjects. Less pressure was recorded for the patients, except for CVA3. Like the healthy subjects, this patient showed double values for the right thumb in comparison with the left thumb.

Table 10. Mean and range of the outcome measures for the task transport an object in the forward (FOR), inward (IN) and outward (OUT) direction. Data is presented for the healthy subjects (mean of 15 subjects), MS (MS 1-3) and CVA (CVA 1-3) patients for the right and left hand. P-values are given to indicate significant influences of directions on the outcome measure.

Outcome measures			HEALTHY mean (SD)		PATIENTS											
					MS1		MS2		MS3		CVA1		CVA2		CVA3	
			L	R	L*	R	L*	R	L*	R	L	R*	L*	R	L*	R
task duration (s)	**FOR**	**mean**	5,39 (1,06)	5,50 (1,16)	-	74,37	12,21	12,54	10,12	8,78	5,66	6,38	8,72	8,8	11,43	9,05
	IN	**mean**	5,54 (1,33)	5,43 (1,22)	25,7	13,78	11,61	12,83	13,43	7,87	6,34	8,11	8,56	8,21	13,57	8,66
	OUT	**mean**	5,43 (1,18)	5,49 (1,17)	46,48	20,54	14,57	12,7	9,22	7,55	5,5	6,69	9,53	7,55	9,47	7,42
	p-value		*0,98*	*1,00*												
wrist ab/ad (°)	**FOR**	**mean**	-7,51 (6,24)	13,62 (6,80)	-	1,00	-4,67	3,67	3,67	11,33	-2,67	10,67	4,33	3,33	-6,00	10,33
		range	-18,36; 4,44	1,53; 26,09	-	-19,00; 1,67	-22,00; 11,67	-7,33; 14,00	-7,67; 16,67	0,33; 24,00	-14,33; 14,33	-7,33; 23,67	-6,67; 11,67	-10,33; 16,33	-15,33; 2,67	1,67; 21,00
	IN	**mean**	-10,29 (7,18)	15,53 (8,71)	-4,67	-4,67	-9,00	4,33	-1,00	18,00	-7,33	14,00	0,33	3,00	-9,33	10,67
		range	-22,82; 4,87	-1,04; 30,40	-20,33; 8,00	-14,00; 6,33	-27,67; 9,67	-8,33; 20,33	-15,33; 18,33	2,33; 39,33	-22,67; 5,67	-0,67; 22,67	-15,33; 10,67	-11,00; 16,33	-18,00; 3,33	-5,00; 22,67
	OUT	**mean**	-4,87 (7,25)	10,44 (6,38)	-9,33	2,33	-4,67	2,00	1,67	9,00	-3,67	14,00	1,33	2,67	-8,00	5,33
		range	-18,07; 7,42	-2,73; 25,89	-29,00; 7,67	-15,67; 19,67	-24,33; 7,33	-10,00; 14,33	-10,00; 16,33	-1,33; 21,67	-9,33; 1,67	5,33; 24,33	-12,67; 13,67	-11,00; 15,67	-12,00; 0,67	-7,00; 18,67
	p-value		*<0,01* §‡	*<0,01* †‡												
wrist fl/ext (°)	**FOR**	**mean**	-24,76 (14,07)	-24,22 (12,34)	-	-22,67	-20,00	-28,00	-31,33	-36,33	-38,33	-41,33	-30,00	-26,00	-30,00	-18,67
		range	-49,20; 4,84	-47,80;2,62	-	-40,67; 0,00	-50,67; 15,00	-55,67; 3,33	-56,67; -5,33	-64,00; 4,67	-57,67; -14,33	-72,33; -0,33	-54,67; 5,33	-71,00; 16,00	-52,33; 1,67	-42,33; 10,33
	IN	**mean**	-24,36 (15,09)	-24,60 (15,30)	-6,00	-11,67	-17,67	-22,00	-22,33	-25,33	-34,00	-44,00	-28,33	-23,00	-25,00	-16,67
		range	-45,18; 3,40	-44,60; 0,09	-22,67; 15,00	-24,00; 2,67	-47,00; 15,00	-55,00; 1,67	-47,67; -3,33	-51,67; 0,33	-53,67; -8,67	-70,67; 0,00	-56,00; 8,00	-58,67; 10,33	-44,33; 1,00	-31,67; 5,00
	OUT	**mean**	-25,60 (14,46)	-24,78 (11,19)	-5,67	-22,33	-24,00	-34,33	-29,67	-32,67	-43,00	-43,33	-26,67	-27,33	-24,33	-17,67
		range	-45,44; 4,42	-42,93; 2,40	-25,67; 15,67	-41,33; -8,67	-52,67; 15,33	-61,00; 2,00	-51,33; -0,67	-58,33; 2,67	-59,67; -19,33	-70,00; -5,00	-51,33; 8,33	-55,33; 14,33	-42,67; 5,67	-34,33; 9,33
	p-value		*0,42*	*0,54*												
forearm sup/pro (°)	**FOR**	**mean**	19,76 (14,26)	-13,00 (14,02)	-	-28,67	28,33	-33,00	17,67	-11,00	16,00	-33,67	19,33	-20,00	38,00	-23,00
		range	12,91; 27,00	-27,02; -13,00	-	-38,67; -14,00	20,33; 37,67	-45,33; -27,00	10,67; 24,33	-18,67; 3,00	12,33; 20,00	-43,33; -23,67	9,67; 27,33	-28,67; -8,33	33,00; 45,00	-29,33; -15,33
	IN	**mean**	23,53 (15,39)	-22,76 (13,71)	33,33	-31,67	31,00	-35,33	20,33	-14,33	19,33	-42,00	28,00	-25,33	42,00	-27,00
		range	15,69; 31,51	-32,20; -15,31	8,33; 72,00	-39,33; -23,00	22,00; 38,67	-44,33; -27,33	15,33; 25,00	-21,00; -9,33	13,00; 29,00	-56,33; -26,67	22,67; 27,33	-37,67; -17,00	38,67; 46,33	-33,67; -19,00
	OUT	**mean**	20,98 (14,20)	-21,11 (12,40)	34,33	-29,67	32,00	-37,00	18,00	-9,00	14,00	-29,00	23,00	-23,00	39,67	-25,00
		range	13,93; 27,84	-27,60; -14,29	5,33; 50,67	-38,00; -20,33	24,67; 40,33	-50,33; -29,67	11,33; 23,00	-16,67; 8,67	9,67; 22,67	-42,67; -16,33	16,00; 26,00	-30,67; -12,67	35,00; 45,00	-30,33; 17,67
	p-value		*<0,01* §†‡	*<0,01* §‡												
pressure thumb (kg/cm^2)	**FOR**	**mean**	0,06 (0,05)	0,14 (0,12)	-	0,03	0,03	0,03	0,00	0,00	0,00	0,10	0,10	0,10	0,10	0,13
		max	0,31 (0,18)	0,64 (0,42)	-	0,37	0,30	0,37	0,13	0,17	0,1	0,50	0,23	0,37	0,37	0,63
	IN	**mean**	0,07 (0,05)	0,15 (0,12)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,10	0,10	0,03	0,10
		max	0,39 (0,21)	0,78 (0,52)	0,03	0,20	0,17	0,20	0,10	0,20	0,10	0,20	0,40	0,50	0,33	0,77
	OUT	**mean**	0,06 (0,05)	0,12 (0,08)	0,00	0,03	0,03	0,10	0,00	0,10	0,00	0,17	0,10	0,10	0,00	0,10
		max	0,29 (0,15)	0,58 (0,38)	0,07	0,27	0,27	0,43	0,10	0,30	0,07	0,83	0,27	0,7	0,27	0,50
	p-value		*0,50*	*0,20*												

* most impaired hand

Friedman test (p < 0,05), post-hoc analysis: Wilcoxon signed-rank test with Bonferroni correction (p < 0,017).

§ Significant difference between the directions forward and inward; † Significant difference between the directions forward and outward; ‡ Significant difference between the directions inward and outward

SD, standard deviation; L, left; R, right; FOR, forward; IN, inward; OUT, outward; abd, abduction; add, adduction; fl, flexion; ext, extension; sup, supination; pro, pronation.

3.3.3 Influence of lifting and transporting an object with one or two hands on outcome measures

Lifting and transporting an object with one or two hands may have an influence on the outcome measures as bilateral activities activate interhemispheric pathways. Therefore, subjects were instructed to lift an object unilateral, bimanual and bilateral. Besides, the same object was transported unilateral en bilateral. Friedman test and Wilcoxon signed-rank test were performed to investigate whether these executions have a significant effect on the outcome parameters in healthy subjects (n=15). Descriptive data of the patients was then compared with the preliminary data of the healthy subjects.

The various executions of lifting an object had no significant influence on the task duration. However, significant values were obtained for wrist abduction/adduction, wrist flexion/extension and forearm supination/pronation (table 11). Wrist abduction/adduction differed significantly between the execution unilateral – bimanual and bilateral – bimanual for both the right and left hand. Bimanual execution showed for the left hand the lowest mean wrist abduction and for the right hand the highest mean wrist adduction. Wrist flexion/extension differed significantly for the left hand between unilateral – bimanual execution. The least extension was observed for the bimanual execution. It was determined that both the right and left hand differed significantly for forearm supination/pronation with the bimanual execution which showed the most mean pronation.

Table 11 shows the mean of the outcome measures for the healthy subjects and patients for the three executions of lifting an object. For MS3, only data for the right hand and for both hands of the bimanual execution are shown. Because of fatigue, this patient was unable to lift the block with his most impaired arm, except for the bimanual execution in which his less impaired arm could assist. It was observed that task duration differed between the executions, but all the executions showed a longer task duration for the patients. No clear patterns between the executions were observed. For instance, bimanual execution resulted in a decrease in task duration for the most impaired arm of CVA1 and no effect on his less impaired arm. In contrast, this execution slowed down both hands of CVA2 and CVA3. In addition, the duration of the bimanual and bilateral execution did not differ for CVA2. Remarkable, MS2 showed a shorter task duration for his most impaired arm compared to his less impaired arm. Bilateral execution was for all the patients the longest task duration. For the outcome measure wrist abduction/adduction, MS2, MS3 and CVA2 used more abduction by their less impaired arm. For this arm, the most abduction was determined for the unilateral execution. More wrist extension was observed for both arms of CVA1. CVA3 showed more extension for his most impaired arm and a decrease for the other arm. Comparable to the healthy controls, most extension was observed for unilateral execution and least for bimanual execution for the less impaired arm.

The most impaired hand showed no clear pattern. More pronation and less supination for both arms were observed for MS2, while CVA3 showed the opposite. Besides, CVA1 showed more pronation and less supination for his most impaired arm while his less impaired arm showed the opposite. In general, most pronation was used for the bimanual execution. The pressure of the thumb was for the less impaired hand higher than the pressure measured in healthy subjects.

Unilateral and bilateral transporting had only a significant influence on the task duration for the left hand of the healthy subjects. The total time to execute the task was significantly shorter for the unilateral than the bilateral execution (table 12).

The task duration of transporting an object unilateral and bilateral showed that the less impaired arm of CVA patients also had a prolonged execution of the task (table 12). In addition, the more impaired arm showed a longer task execution compared to the less impaired hand. However, this clear distinction declined with bilateral execution. Besides, it was observed that bilateral execution was always longer than unilateral execution. Comparable results to the healthy subjects were obtained for the outcome measure wrist abduction/adduction. Only MS1 showed clearly less abduction for his most impaired hand while CVA3 showed more abduction for his less impaired hand. For both hands, half of the patients used more abduction for the unilateral execution. 3 patients showed more extension and less flexion with their most impaired arm. Only MS1 showed an increase of flexion for both hands compared to the healthy subjects. In addition, half of the patients showed less flexion with their less impaired arm. 4 patients showed more pronation for their most impaired arm. It was observed for the less impaired arm that MS1 and MS2 used more pronation while MS3 and CVA1 used less pronation. CVA2 and CVA3 showed comparable results to the healthy subjects. Unilateral or bilateral execution was not associated with more or less pronation. For 4 patients, more pressure of the thumb was measured for the less impaired arm compared to the more impaired arm.

Table 11. Mean and range of the outcome measures for the task lift an object unilateral (UNI), bilateral (BI) and bimanual (BIM). Data is presented for the healthy subjects (mean of 15 subjects), MS (MS 2, 3) and CVA (CVA 1-3) patients for the right and left hand. P-values are given to indicate significant influences of lifting with one or two hands on the outcome measures.

Outcome measures			**HEALTHY mean (SD)**		**PATIENTS**									
					MS2		**MS3**		**CVA1**		**CVA2**		**CVA3**	
			L	**R**	**L***	**R**	**L***	**R**	**L**	**R***	**L***	**R**	**L***	**R**
task duration (s)	**UNI**	**mean**	6,12 (1,24)	6,14 (1,20)	13,27	14,25	-	8,5	7,57	8,6	9,45	8,2	12,55	11,24
	BI	**mean**	6,20 (1,23)	6,18 (1,25)	14,75	14,89	-	-	9,01	9,05	10,42	9,71	14,42	14,16
	BIM	**mean**	5,90 (1,10)	5,90 (1,10)	13,21	13,24	16,73	16,12	7,49	7,64	10,42	9,77	12,89	12,89
		p-value	*0,33*	*0,10*										
wrist abd/add (°)	**UNI**	**mean**	4,62 (7,37)	0,98 (6,16)	10,67	-8,33	-	-3,33	6,00	-3,33	3,67	-7,33	12,00	-0,33
		range	-4,51; 14,51	-8,71; 9,84	3,33; 17,67	-18,33; 2,33	-	-10,33; 6,00	-3,67; 13,33	-15,00;11,00	-4,00; 13,00	-15,33; 0,33	0,67; 23,67	-7,33; 5,67
	BI	**mean**	5,64 (7,26)	-0,24 (5,30)	10,67	-6,67	-	-	8,67	-3,00	1,33	-4,33	9,67	0,33
		range	-3,47; 14,40	-10,24; 9,44	3,33; 16,33	-17,00; 0,00	-	-	-5,67; 20,00	-12,00; 13,67	-9,00; 9,33	-12,33; 2,33	1,00; 19,67	-8,33; 9,67
	BIM	**mean**	3,40 (7,20)	2,30 (5,20)	11,00	-6,33	3,67	-2,67	5,67	-1,67	2,67	-4,33	9,33	1,67
		range	-5,70; 13,20	-7,40; 11,70	3,33; 19,33	-15,00; 1,00	-4,33; 8,00	-17,00; 12,67	-5,33; 13,67	-12,33; 13,67	-5,33; 13,00	-16,33; 10,67	0,00; 19,33	-7,67; 9,33
		p-value	*<0,01* [§‡]	*<0,01* [§‡]										
wrist fl/ext (°)	**UNI**	**mean**	-3,67 (9,81)	-5,60 (9,56)	-2,33	-8,67	-	-10,67	-39,67	-31,33	-3,00	-1,67	-6,67	9,00
		range	-25,82; 18,73	-27,04; 18,16	-32,67; 17,00	-33,67;10,33	-	-28,33; 12,00	-56,33; -15,67	-72,33; -2,33	-24,33; 15,00	-28,67; 19,00	-38,00; 22,33	-16,67; 33,33
	BI	**mean**	-2,40 (10,45)	-4,27 (8,56)	-1,00	-8,33	-	-	-33,67	-30,00	-3,33	3,33	-9,67	9,00
		range	-22,53; 18,56	-23,36; 17,09	-21,33; 16,67	-27,33; 8,00	-	-	-54,00; -10,33	-72,00; -0,67	-33,67; 15,33	-20,33; 19,33	-41,67; 17,67	-16,00; 31,00
	BIM	**mean**	-1,50 (10,30)	-3,90 (8,50)	2,00	-6,33	-28,33	-16,33	-33,00	-33,33	-0,33	4,00	-7,33	9,67
		range	-20,40; 17,80	-22,20; 16,60	-21,33; 15,33	-30,00; 7,00	-51,33; -10,33	-38,00; 4,33	-56,00; -12,33	-70,67; -2,00	-20,67; 16,67	-17,67; 19,33	-37,33; 15,67	-14,67; 29,33
		p-value	*0,03* [§]	*0,08*										
forearm sup/pro (°)	**UNI**	**mean**	5,40 (11,94)	-3,04 (11,47)	19,33	-22,33	-	0,67	-4,00	-14,67	6,00	-5,00	-5,67	11,00
		range	-11,40; 24,20	-22,09; 13,64	0,33; 37,67	-42,00; -5,67	-	-12,00; 12,00	-25,00; 15,33	-41,33; 5,00	-13,67; 24,67	-26,67; 16,33	-20,67; 9,67	-7,33; 25,00
	BI	**mean**	5,38 (12,02)	-2,67 (10,79)	20,67	-22,33	-	-	-4,00	-14,00	7,00	-5,00	-7,00	9,00
		range	-10,58; 23,44	-21,47; 12,96	5,33; 33,00	-39,00; -8,00	-	-	-24,67; 21,00	-41,33; 3,67	-14,00; 26,33	-25,33; 19,00	-21,67; 8,67	-4,33; 23,00
	BIM	**mean**	7,70 (12,30)	-5,20 (11,10)	22,00	-23,00	11,33	-3,333	0,00	-17,67	10,67	-6,33	-6,00	9,67
		range	-6,10; 23,70	-21,60; 8,90	6,33; 37,00	-37,33; -9,00	-1,33; 19,00	-14,67; 10,33	-20,00; 17,33	-43,00; 2,67	-10,67; 26,33	-25,33; 17,33	-19,33; 9,00	-4,00; 20,67
		p-value	*<0,01* [§‡]	*<0,01* [§‡]										
pressure thumb (kg/cm^2)	**UNI**	**mean**	0,00 (0,01)	0,03 (0,06)	0,00	0,10	-	0,00	0,07	0,10	0,00	0,10	0,00	0,00
		max	0,06 (0,07)	0,19 (0,21)	0,00	0,57	-	0,13	0,20	0,30	0,20	0,43	0,03	0,00
	BI	**mean**	0,07 (0,11)	0,05 (0,06)	0,00	0,10	-	-	0,13	0,10	0,00	0,10	0,00	0,00
		max	0,00 (0,00)	0,02 (0,04)	0,00	0,43	-	-	0,50	0,33	0,23	0,50	0,00	0,07
	BIM	**mean**	0,00 (0,00)	0,00 (0,00)	0,00	0,00	0,00	0,00	0,10	0,07	0,00	0,10	0,00	0,00
		max	0,10 (0,10)	0,10 (0,00)	0,00	0,17	0,00	0,17	0,47	0,30	0,10	0,57	0,07	0,17
		p-value	*1,00*	*0,07*										

* Most impaired hand

Friedman test (p < 0,05), post-hoc analysis: Wilcoxon signed-rank test with Bonferroni correction (p < 0,017).

§ Significant difference between the executions unilateral - bimanual; † Significant difference between the executions unilateral - bilateral; ‡ Significant difference between the executions bimanual and bilateral.

SD, standard deviation; L, left; R, right; UNI, unilateral; BIM, bimanual; BI, bilateral; abd, abduction; add, adduction; fl, flexion; ext, extension; sup, supination; pro, pronation.

Table 12. Mean and range of the outcome measures for the task transport an object unilateral (UNI) and bilateral (BI). Data is presented for the healthy subjects (mean of 15 subjects), MS (MS 1-3) and CVA (CVA 1-3) patients for the right and left hand. P-values are given to indicate significant influences of transporting with one or two hands on the outcome measures.

Outcome measures			HEALTHY mean (SD)		PATIENTS											
					MS1		MS2		MS3		CVA1		CVA2		CVA3	
			L	R	L*	R	L*	R	L*	R	L	R*	L*	R	L*	R
task duration (s)	UNI	mean	5,18 (1,11)	5,35 (1,15)	13,04	10,07	10,19	9,29	9,98	5,96	5,62	7,34	7,19	6,62	11,69	11,18
	BI	mean	5,68 (1,29)	5,67 (1,28)	16,44	17,05	10,93	10,6	18,05	16,98	8,07	8,17	8,78	8,36	12,57	12,6
		p-value	*0,03* †	*0,21*												
wrist ab/add (°)	UNI	mean	9,11 (7,39)	-2,44 (5,71)	1,33	-9,33	16,67	-10,67	14,00	-4,00	12,33	-5,33	6,33	-14,00	9,00	-9,00
		range	-0,60; 19,00	-13,07; 7,38	-3,67; 8,33	-15,00; -2,67	10,00; 23,00	-17,67; -2,00	6,00; 21,00	-11,67; 9,00	3,00; 21,00	-16,67; 5,67	1,00; 14,00	-22,00; -7,00	-2,67; 19,00	-28,33; 10,33
	BI	mean	9,42 (8,04)	-4,00 (6,00)	3,67	-7,33	16,67	-7,67	9,00	-5,00	11,67	-7,33	2,00	-11,00	11,00	-12,33
		range	0,33; 18,96	-12,07; 4,76	-3,00; 12,67	-13,67; 0,00	11,00; 25,00	-17,00; 2,00	0,00; 18,33	-13,00; 9,00	0,00; 21,00	-15,33; 5,67	-5,67; 6,33	-16,67; -4,00	0,33; 18,33	-28,67; 7,33
		p-value	*0,47*	*0,25*												
wrist fl/ext (°)	UNI	mean	4,27 (8,62)	0,56 (9,83)	9,00	2,00	2,67	-4,67	-9,67	-7,00	-29,67	-21,33	1,33	4,33	-11,33	-4,33
		range	-10,80; 21,27	-15,67; 19,11	-12,33; 31,67	-17,00; 29,67	-19,00; 15,00	-20,67; 6,67	-24,67; 2,67	-23,67; 5,67	-47,67; -13,00	-39,33; -1,33	-12,33; 18,00	-11,67; 19,67	-32,67; 7,67	-29,67; 15,00
	BI	mean	4,33 (10,18)	1,40 (9,63)	13,00	1,67	4,00	-2,67	-19,33	-8,67	-28,33	-22,00	5,67	7,33	-10,00	-9,33
		range	-9,13; 19,71	-10,69; 15,78	-4,67; 30,00	-16,33; 22,67	-13,00; 17,33	-14,00; 3,67	-31,67; -7,67	-17,67; 1,33	-43,33; -13,67	-33,67; -5,67	-6,00; 20,00	-8,67; 19,67	-25,67; 7,33	-30,33; 9,00
		p-value	*0,66*	*0,08*												
forearm sup/pro (°)	UNI	mean	11,64 (11,99)	-7,87 (12,13)	22,33	-18,00	25,00	-24,67	12,67	-3,33	2,67	-21,00	8,00	-13,33	28,33	-12,67
		range	1,44; 24,71	-23,07; 4,13	6,00; 44,33	-34,00; -6,00	9,33; 39,33	-37,33; -17,33	6,33; 19,67	-13,00; 4,33	-8,33;15,33	-43,33; -8,67	-7,33; 26,67	-27,67; -1,00	18,33; 40,00	-26,00; -1,67
	BI	mean	11,62 (11,31)	-7,78 (11,24)	17,33	-19,00	24,67	-26,00	13,67	-3,33	4,33	-21,00	8,33	-11,67	28,67	-15,00
		range	1,27; 25,20	-21,47; 1,80	-0,33; 39,00	-29,67; -2,96	12,67; 37,00	-37,33; -17,00	4,33; 20,33	-13,00; 6,00	-5,67; 16,67	-41,00; -9,33	-7,33; 30,00	-25,67; 1,00	14,33; 40,00	-25,00; -9,33
		p-value	*0,38*	*0,61*												
pressure thumb (kg/cm^2)	UNI	mean	0,00 (0,00)	0,01 (0,03)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,10	0,00	0,10	0,07	0,00
		max	0,02 (0,04)	0,08 (0,11)	0,00	0,40	0,00	0,20	0,03	0,13	0,10	0,33	0,13	0,43	0,27	0,03
	BI	mean	0,00 (0,00)	0,01 (0,03)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,10	0,03	0,10	0,00	0,00
		max	0,02 (0,04)	0,06 (0,09)	0,00	0,00	0,00	0,20	0,03	0,20	0,13	0,47	0,20	0,53	0,23	0,00
		p-value	*1,00*	*1,00*												

* most impaired hand

Wilcoxon signed-rank test ($p < 0,05$).

† Significant difference between the executions unilateral - bilateral

SD, standard deviation; UNI, unilateral; Bi, bilateral L, left; R, right; abd, abduction; add, adduction; fl, flexion; ext, extension; sup, supination; pro, pronation.

3.3.4 Correlation of clinical measurements with task duration

Clinical measurements may give an idea of the underlying functions necessary to execute the tasks. Therefore, Spearman correlations were calculated for the clinical measurements with the task duration (table 13). Data of five patients were used in the analysis because the clinical measurements could not be assessed for one patient due practical issues. High correlations were observed for the motricity index with the lifting tasks for both the right and left hand, except for the task lifting in the bimanual condition. The left hand showed very high correlations for the JAMAR dynamometer with all the tasks except for the tasks executed in the inward direction. For the right hand, only high correlations were observed for the task in which an object was transported in different directions. Diverse results were obtained for the key grip. Three jaw grip and tip-to-tip grip showed comparable results. They correlated well for the left hand with the task in which an object was lifted in different directions and for the right hand with the task lift an object executed in bimanual and bilateral condition. Unexpected, low correlations were obtained for the ARAT. Only the task transport in the forward direction and the tasks lift an object unilateral and bilateral showed high correlations with the left hand. The subscore of the ARAT, the ARAT 5-finger grip showed for the tasks in different directions a good correlation for the right hand. In addition, the tasks lift an object unilateral and bilateral showed also good correlations for both hands. For the 9HPT, only significant correlations were visible for the left hand for the tasks lift and transport an object in the inward direction and the task transport an object in different execution conditions. However, due to the small patient sample, only correlations greater than or equal to 0.900 were significant.

3.3.5 Comparison of the phase durations between the healthy, less and more impaired arm

The total duration of the tasks differed between healthy subjects and patients. Therefore, it was investigated whether particular phases were prolonged in patients. The durations of the phases of the task in which an object was lifted in unilateral, bimanual and bilateral condition are presented in figure 4.

Healthy subjects showed no differences between their dominant and non-dominant hand. In addition the standard deviation of the mean of the phases were also small, indicating less variability among the subjects. Similar results for the three executions of the patients were obtained. Differences between the impaired and less impaired hand were observed although prolonged durations were found for both hands of the patients for the phases reaching, lifting, putting down and retrieving compared to the healthy subjects. Besides, the bilateral execution condition showed also a somewhat longer duration for the grasping and release phase.

Table 13. Spearman correlations of task duration with clinical measures for the right and left hand of the patients (n=5).

task			motricity index		JAMAR		key grip		three jaw grip		tip to tip grip		ARAT		ARAT 5-finger grip		9HPT	
			L	**R**	**L**	**R**	**L**	**R**	**L**	**R**	**L**	**R**	**L**	**R**	**L**	**R**	**L**	**R**
DIR	**lift**	**forward**	-1,000*	0,738	-0,800	-0,400	-0,800	0,000	-0,800	-0,400	-0,800	-0,400	-0,400	-0,316	0,000	-0,775	0,500	0,000
		outward	-1,000*	0,738	-0,800	-0,200	-0,800	0,400	-0,800	0,200	-0,800	0,200	-0,400	-0,632	0,000	-0,775	0,500	-0,400
		inward	-0,800	0,738	-0,400	-0,400	-0,400	0,000	-1,000*	-0,400	-1,000*	-0,400	-0,200	-0,316	0,000	-0,755	1,000*	0,000
	transport	**forward**	-0,400	-0,154	-0,800	-0,700	0,000	-0,500	-0,200	-0,400	-0,200	-0,700	-1000*	-0,564	-0,894	-0,783	0,500	0,500
		outward	-0,564	-0,410	-0,900	-0,900*	-0,500	-0,800	-0,300	-0,700	-0,300	-0,900*	-0,700	-0,564	-0,632	-0,783	0,800	0,800
		inward	-0,616	-0,154	-0,600	-0,600	-0,400	-0,300	-0,700	0,000	-0,700	-0,400	-0,300	-0,718	-0,316	-0,783	1,000*	0,300
EXE	**lift**	**unilateral**	-1,000*	0,738	-1,000*	-0,200	-0,500	0,400	-0,500	0,200	-0,500	0,200	-1,000*	-0,632	-0,866	-0,775	0,500	-0,400
		bimanual	-1,000*	-0,105	-0,800	-0,600	-0,500	-0,800	-0,800	-1,000*	-0,800	-1,000*	-0,400	0,211	0,000	-0,258	0,500	0,800
		bilateral	-1,000*	0,500	-1,000*	-0,500	-0,800	-0,500	-0,500	-1,000*	-0,500	-1,000*	-1,000*	-0,500	-0,866	-0,866	0,500	0,500
	transport	**unilateral**	-0,462	0,359	-0,700	0,100	-0,300	0,300	-0,400	0,300	-0,400	0,000	-0,600	-0,103	-0,632	-0,224	1,000*	-0,300
		bilateral	-0,462	-0,051	-0,700	-0,300	-0,300	-0,100	-0,400	0,100	-0,400	-0,300	-0,600	-0,359	-0,632	-0,447	1,000*	0,100

*p-value < 0,05
**p-value < 0,001
DIR, direction; EXE, execution; L, left; R, right; ARAT, action research arm test; 9HPT, nine-hole peg test

Conclusions cannot be made about the duration of the phase pregrasping as it was very difficult to determine the start of this phase. Therefore, it was analyzed whether this phase was present in the patients or not. For some of the patients, no differences were observed in comparison with the healthy subjects. However, CVA3 and MS3 showed no pregrasping phase with their most impaired hand. Furthermore, this phase was not present for both hands of MS1. The graphs also showed that more variability was observed for the patients.

When lifting is compared between the three executions, no differences were observed for the healthy subjects while the patients showed a few differences. Bilateral execution showed in comparison with the unilateral execution a longer duration for reaching, lifting and putting down phase for both hands of the patients. Besides, this execution seemed to prolong the duration of the grasp phase for their both hands. In addition, bimanual execution resulted in a prolongation of the phase lifting for the less impaired arm and no difference for the more impaired arm. Also, the phase duration of putting down was decreased for the most impaired hand and slightly increased for the less impaired hand compared to unilateral execution. In addition, retrieving was longer for the most impaired arm for this condition.

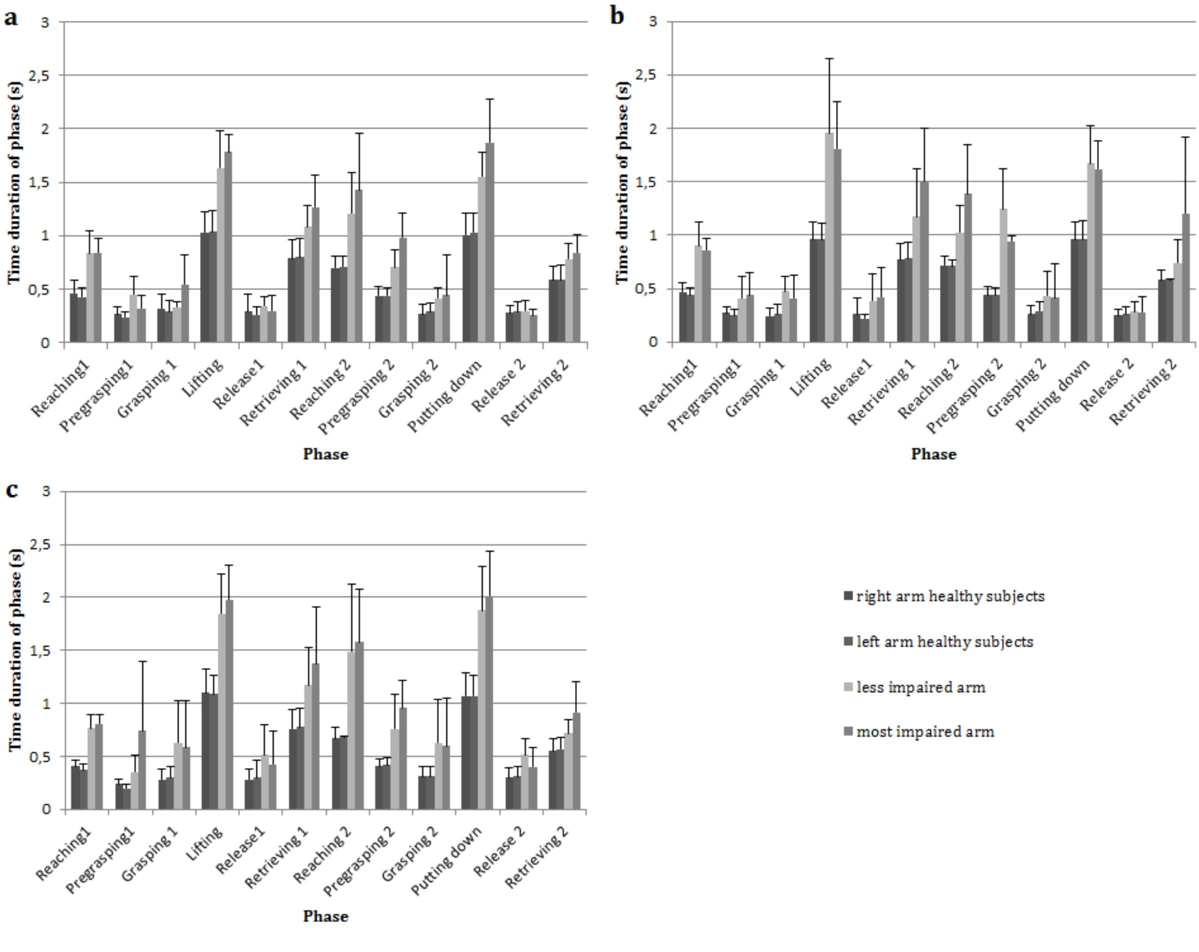

Figure 4. Time duration of the different phases for the task lift an object (**a**) unilateral, (**b**) bimanual and (**c**) bilateral. Data is shown for the healthy controls (n=15) and patients (n=5).

4 Discussion

This study used a consumer-friendly and portable movement analysis system, CAPTIV-L7000 to investigate the distal movements of the upper limbs. The performances of the upper limbs for both unilateral and bilateral functional tasks were observed in 15 healthy subjects. In addition, as pilot study, this was also determined in a small study sample of 3 MS and 3 CVA patients. It was first investigated whether this measuring system has the potential to be used as an objective evaluation tool for the arm function during the execution of functional tasks. Therefore, the intra-subject and test-retest intra-rater reliability was examined. Then, this study investigated the influence of hand dominance, different directions and execution conditions on the movement characteristics. In addition, previous research questions were also explored for the patient sample and their data were compared to the reference data of the healthy subjects.

4.1 Intra-subject variation

The intra-subject variation was examined in both the healthy and patient group. The results showed that the three middle executions of the tasks were performed consistent by all the subjects. In contrast to most studies which addresses the kinematics of a non-functional task, we determined movements in which an object was manipulated. Therefore, more variation could be expected, however this was not observed in healthy subjects. Moreover, healthy subjects showed very high correlations for all the outcome measures. First of all, this suggests that the instructions of the tasks were clear. Besides, the tasks were simple with a well-defined start and end. In addition, the subjects were instructed to practice the tasks twice to make them familiar with the tasks. This experimental procedure resulted in less mistakes during the performances and thus more consistent movements. The outcome parameter task duration showed very high correlations in the healthy group. This parameter was obtained by coding of the video's, so high correlations also indicate consistent coding of begin and end phases of the tasks. Also the sensor data was very consistent on both arms. This points out the high reliability of the measuring system that was used in this study. ICC of the pressure sensors showed good correlation for the thumb but more variable results for the index and middle finger. This indicates that during the three executions similar maximum pressure was used by the thumb while this differed for the index and middle finger. A possible reason for these differences in the consistency of the fingers is that the thumb was the main contributor to the force required to lift, put down or transport the block. ICC of the maximum and not the mean pressure was calculated, because a very low mean pressure was found, which was not surprising, as only a minor part of the task required the grasp of the object. Comparison of the consistency of the healthy subjects with the patients showed slightly higher correlations for the outcome parameters task duration and wrist abduction/adduction for the healthy subjects. More intra-subject variation in task duration in patients can be explained by the observation that patients had sometimes more difficulties to grasp the block. One reason for this was observed higher tension in the hand muscles and therefore more difficulties to open the hand to grasp the block. Lower correlation for wrist abduction/adduction may suggest more variable movements. Compared to the healthy subjects, also lower correlations for the pressure of the thumb were observed for the patients while the correlations for the pressure of the middle finger were higher for the task executed in different directions. The handgrip used for this task required mainly the involvement of the thumb, index finger and middle finger. This may suggest that healthy subjects mainly used their thumb in this handgrip and divided the pressure between the other fingers randomly. In contrast, patients may have used mainly the thumb and middle finger to grasp and transport the object. This is consistent with a study in which they observed in stroke patients a high involvement of the thumb and middle finger in force generation [37]. For the same tasks, the healthy subjects showed more variable ICC's of the pressure of the index finger compared to the patients. This can be explained by the observation that the healthy subjects did not used always the index finger in this handgrip in contrast to the patients.

4.2 Intra-rater reliability

Use of movement analysis for repeated evaluation of the deficits of patients with upper limb dysfunction in longitudinal studies or intervention studies, requires reliable outcome parameters. It is important to have the certainty that observed deviations from the normal population are not due to measurement errors, but instead are real differences. Therefore, the reliability of quantifying the performance was determined by a test-retest design. The reliability of the outcome parameters is influenced by various potential sources of errors. For instance the sensor placement and calibration method. However, this was kept to a minimum by using a very standardized protocol. Only the pressure sensors were difficult to place as these sensors had a very small surface and two different handgrips were used in this study. Another source of error may be the subjects themselves who may show variability in their performances. But in our study, this did not influence much the reliability as intra-subject variation was shown to be excellent, except for the pressure sensors, which may partly explain their low reliability. Besides also the rater can be a source of error. However, the same rater performed the placement and calibration protocol and gave the instructions which should minimize additional error. Furthermore, sources which cannot be lowered are the measurement system itself and skin movements. The measuring system used in this study had an inaccuracy of 2°. In addition, video fragments were sampled at 25 Hz, which may result in error of 40 milliseconds in the task duration and coding of the phases. Besides, there was also a discrepancy between the video fragments and the sensor data as the sensor data was sampled at 32 Hz. Despite, these various sources of errors, in general, good to excellent ICC's were obtained for all the outcome measures except for the pressure sensors and wrist abduction/adduction. Also the SEM was presented, which provides an estimate of the measurement error size that can be expected when the observation is repeated by the same observer on a different time occasion. No definitions exist in literature about SEM, however we defined a SEM below 7° for the joint angles as good which indicates that only forearm pronation/supination showed a slightly lower reliability (SEM ranging between 6.23 – 7.57) [52]. The outcome parameters, wrist abduction showed a lower ICC for some tasks. However, the SEM's were good, ranging between 3.03° and 5.67°. It has been demonstrated that ICC, in contrast to SEM is affected by between-subjects variability. Therefore, these ICC's must be interpreted with caution [51]. This suggests that the parameter wrist abduction/adduction is also reliable. So as a conclusion, besides the pressure sensors, the reliability of evaluation was good.

4.3 Influence of hand dominance on outcome measures

The influence of hand dominance was investigated to assure that differences between the less impaired and more impaired arm in patients was due to the impairment and not of hand dominance. Healthy persons showed significant differences between the dominant and non-dominant hand for the outcome measure wrist abduction/adduction for all the tasks and related conditions. In addition, for the task transport an object unilateral, a longer task duration for the right hand was observed. The tasks were always first executed with the right hand which may have resulted in a better familiarization of the tasks and consequently in a more rapid performance of the left hand. It is however remarkable that only one specific task execution appeared different between the hands. Another observation was that for the tasks executed in different directions, on average double values for the pressure of the thumb were obtained for the right hand compared to the left hand. A possible explanation is that the dominant hand of the healthy persons has more strength. A study investigated the effect of hand dominance on the grip strength by 128 right and 21 left handed healthy subjects. The grip and pinch strength was measured by the JAMAR dynamometer and manual pinchmeter respectively. It was concluded that only right-handed subjects had a significant stronger dominant hand compared to the non-dominant hand. The healthy subjects that participated in this study were all right hand dominant, so our results are in line with the study. It was also reported that the strength scores of the right hand were 8.20% higher compared with the left hand. Other studies reported a difference of 12.7% [53]. Another possibility was that a slightly different handgrip was used by the right and left hand, although this could not be observed. For the tasks performed in different execution conditions, this effect was not observed. Perhaps, the different handgrip of these tasks resulted in a more divided pressure over all the fingers, i.e. force deficit effect [37].

4.4 Influence of moving in different directions on outcome measures

Literature suggests that movements in some directions are more difficult to perform for patients due to movement synergies, asymmetry in severity of muscle weakness between agonists and antagonists and disruption of interjoint coordination [39, 43]. Therefore, it was first investigated whether there were significant differences in outcome parameters between the directions inward, forward and outward in healthy subjects. Then, this reference data was exploratively compared with preliminary data of the patient group.

Similar results were obtained for the lifting and transporting task. It was demonstrated that directions had a significant influence on the outcome measures wrist abduction/adduction and forearm supination/pronation. For both hands, it was observed that most mean adduction was used for the inward direction, while outward used the least mean adduction. The direction inward was also associated with the most mean pronation for both the right and left hand. Keeping in mind the handgrip that was used, these results were expected. Pressure of the thumb was significant different between the direction forward and inward. Highest pressure was used for the direction inward, least for the direction forward. As a conclusion, these results show that for the inward direction the most pronation, adduction and pressure of the thumb was used by the healthy subjects. This suggests that the inward direction requires the largest range of motion. This is consistent with studies in stroke patients which demonstrated that contralateral and far targets were more difficult to execute [42].

Patients showed for all the directions of the tasks lifting and transporting an object a longer task duration with their more impaired arm compared to their less impaired arm and the healthy subjects. In addition, the so-called non-affected arm of stroke patients also showed a prolonged task duration in comparison with the healthy subjects. This is in line with studies demonstrating that stroke, besides to contralateral deficits, also results in ipsilateral deficits. A study in which stroke patients were instructed to transport a stylus from one target to another, showed that the movement time was significantly longer for both the ipsilateral and contralateral upper extremity compared to the healthy subjects. Moreover, the movement times of both arms did not differ significantly [54]. It was also earlier demonstrated that these deficits are present, even when no or less upper limb impairment is detected by clinical measurements ipsilateral of the brain lesion [55]. Also the stroke patients that participated in this study had good clinical scores on the clinical measurements for their less impaired arm. A possible explanation is derived from the observation that in young healthy subjects, unilateral movements lead to the activation of both hemispheres, which was assessed by brain imaging. Activation was more apparent when the task was complex [54]. Although in this study well-defined tasks were used. It was observed that the patients and even some healthy subjects had difficulties to remember the direction of execution or the sequence of movements. It is suggested that unilateral movements activate transcallosal pathways. Consequently, when one hemisphere is damaged, the communication between the hemispheres is disrupted and this results in deficits of both upper extremities [54].

For the tasks executed in different directions, less wrist adduction was showed for the impaired and less impaired arm for the lifting tasks, while this was mostly observed for the transporting task only for the less impaired arm. Furthermore, half of the patients demonstrated more pronation with their most impaired arm. Contrasting results were obtained for wrist flexion/extension as some subjects showed more extension, while other showed a decrease or similar results to the healthy subjects. Also more flexion was observed for some patients in both upper limbs. The tasks that were performed by the subjects required extension of the upper limb. The synergy pattern of extension is associated with shoulder extension and adduction, forearm pronation and wrist flexion [56]. According to this synergy pattern, that occur early in the recovery of stroke patients, one should expect that more pronation and wrist flexion would be observed. However, more wrist extension was observed for some patients. Moreover, the patients who showed more pronation did not show more flexion. An explanation is that our patients showed only mild dysfunction of their upper extremities. Especially the stroke patients were good recovered from their stroke which can be determined from the clinical scores. One inclusion criteria of this study was that patients had to be able to grasp a block. Therefore, patients who had severe arm dysfunction could not participate and only more recovered patients were included in this study. Besides, this is a pilot study, so only a few patients were analyzed. Another explanation is that the distal joints and muscles may be less impaired than the proximal part of the upper limb. Most studies have concentrated on the proximal part and less is known about the impairment of the distal part. However, one study showed that for the less impaired hand, the wrist extension strength was less impaired than shoulder abduction strength [57]. The patients showed, in agreement with the healthy subjects, the highest values of pronation and adduction for the inward direction confirming that this direction requires the largest range of motion.

4.5 Influence of lifting and transporting an object with one or two hands on outcome measures

It is still unclear whether bimanual and bilateral interventions improves the upper limb function or contrasting, results in a worse performance of the less impaired arm or both arms. Nowadays, bilateral training is assumed to be a higher level training requiring more higher cognitive functions. A better understanding of the movement characteristics used for these executions is necessary. Therefore, the influence of different executions of the lift and transport tasks on the outcome parameters were analyzed. Data of healthy controls were compared with preliminary data of the patients.

Unexpectedly, in healthy subjects, lifting with one or two hands had no influence on the task duration, but a significant influence on the joint angles. During bimanual execution, the right hand used the most adduction and the left hand used the least abduction in comparison with the other executions. Forearm supination/pronation showed significant more pronation in the bimanual execution. Bimanual lifting of the block may have resulted in a slightly changed handgrip. Subjects may have grasped the block more above in the corners than side wards in the middle of the block compared to the other executions. This may also explain why less extension was measured in the bimanual execution. Although a significant difference was only founded for the left hand, it was noted that the right hand followed with a trend towards significance. Transporting with one or two hands had only a significant influence on task duration of the left hand. More time was needed to transport the block with two hands compared with one hand. As a conclusion, the results suggest that bimanual execution compared to unilateral and bilateral execution results in more wrist adduction, less wrist extension and more forearm pronation which should be easier to execute by patients than the other executions. However, all these observed differences were very small, only a few degrees.

The descriptive data of the patient group showed a prolonged task duration compared to the healthy subjects for both hands. The most impaired hand showed a longer duration compared to the less impaired hand except for MS2. This patient showed a relatively shorter task duration with his most impaired arm. Clinical scores of this patient show that there was no large difference in impairment between the right and left upper limb. Bimanual and bilateral execution resulted in a decrease of the difference in task duration between the more impaired and less impaired upper limb. Our results are supported by a study of Steenbergen et al. who investigated movement time in children with CP. The children had to lift an object unilateral and bimanual. They also observed that the more impaired hand had a significant longer duration time than the less impaired hand. However bimanual execution diminished this difference [45]. Contrasting results among the patients were obtained in respect to the duration of bimanual execution. In one patient, task duration of the most impaired arm decreased, while no effect was observed for the less impaired hand. On the other hand, an increase in duration for both hands was observed for three other patients. Our results reflects the vagueness about bimanual execution. Some studies show a positive effect on the task duration of the impaired hand and no effect on the less impaired hand, while others show a negative effect for both arms. Steenbergen et al. showed that bimanual lifting resulted in a prolongation of total task duration of the less impaired hand and a little increase for the impaired hand [45]. In addition, two other studies examined the bimanual coordination with a spatially symmetric motor tasks. They reported an 11% and 18% increase in movement duration for the paretic and less paretic limb respectively during the bilateral execution compared to the unilateral execution [58]. On the other hand, a study in patients with chronic hemiparesis demonstrated that simultaneous movements resulted in a decrease of the movement duration of the paretic limb, while it had no influence or an small increase of movement time on the non-paretic limb [44]. Bimanual execution may facilitate the movement of the most impaired arm. Some authors suggest that during unilateral task execution, the cortical hemisphere that gives stimulating input to the limb, inhibits the other cortical hemisphere so that no mirror movement can occur. During bilateral movements, the opposite would occur which may result in an improved performance of the more impaired limb [44].

Bilateral execution resulted in a longer task duration compared to unilateral or bimanual execution for both the patients and the healthy subjects. Our results showed that the paretic limb slowed down the performance of the less impaired arm which is also stated by others [58, 59]. It has been suggested that bilateral movements require the interaction of both hemispheres to coordinate the action of the limbs. This interaction may be time-consuming and consequently results in increased movement times for the bilateral tasks which may also explain why bimanual execution can result in longer movement times [59]. Besides, the visuospatial and attentional demands of the task may also slow down the performance of the less impaired limb. In particular, our task required the coordinated movement of each limb to place the block at its end position, which is more difficult compared to a non-functional tasks without object manipulation and precise endpoint positions, like reaching. Moreover, it has been suggested that the visuospatial and attentional demands mainly activate the right hemisphere [41]. As 5 out of the 6 patients were more impaired on the left side, this may also have contributed to the increased task duration. In addition, patients were first instructed to perform the unilateral execution. When they were able to perform this condition, also the bimanual and bilateral executions were performed. Unilateral execution may have resulted in fatigue which lead to longer movement times during bimanual and bilateral execution. In the future, it is recommended to give a break between these executions and to randomize the conditions to be sure that the differences between the executions are not due to fatigue.

Messier et al. showed that bilateral execution resulted in an increase of shoulder abduction, trunk flexion and a decrease of elbow extension. They concluded that bilateral execution did not improve the performance of the more impaired limb. In addition, the performance of the less impaired arm also decreased [41]. However, comparison between the executions revealed no clear patterns. Data of the sensors showed for wrist abduction/adduction comparable results with the healthy subjects or an increase in abduction for the less impaired arm. More extension was observed for the more impaired arm for the execution task transport an object. For both tasks more pronation was also observed for the more impaired arm for some patients. These results are similar as those obtained for the tasks executed in different directions.

4.6 Correlations of clinical measurements with task duration

Correlations of the clinical measurements with task duration were calculated in the patient group in order to find out which characteristics such as fine motor control and strength determine movement time of the functional tasks. The results of this pilot study show only high correlations for the motricity index and the JAMAR dynamometer with task duration suggesting that strength is an important determinant for the ability to lift an object. This is in agreement with a study by Zackowski et al. which demonstrated that the velocity of task execution is determined for 58% by the strength of the upper limb. Therefore, a lower strength results in slower movements [47]. The ARAT and the 9HPT did not show high correlations. The ARAT 5-finger grip showed high correlations for the tasks executed in different directions only for the right hand. The low correlations of the left hand are probably due to more variation amongst the subjects in the ARAT 5-finger score and in the task duration of this hand.

4.7 Comparison of the phase durations between the healthy, less and more impaired arm

The total duration of the tasks were prolonged for both arms in patients. In order to elucidate which of the phases showed a longer duration, the time durations of the phases of the task lift an object unilateral, bimanual and bilateral were compared between the patient and healthy group.

In general, it was determined that all the phases had a very short duration. However, a clear prolongation was observed in the patients for the phases reaching, lifting, putting down and retrieving in comparison with the healthy subjects. Not much articles have determined the phases of tasks in detail like this study. One study in developing children with CP investigated the phases of bringing a glass to the mouth. This task was broken down in reaching, grasping, transport 1 (bring glass to mouth), transport 2 (put glass back on table), release and return. Consistent with our study, the transport phases were the longest. In comparison with the healthy children, longer durations were observed for all the phases, but only the grasp and release phase showed a significant longer duration. However, these latter phases were also associated with the most variation amongst the children with CP [60]. Our results did not show differences for these phases between the healthy and impaired subjects, except for the task lift an object bilateral. However, in line with the study in CP, high variability was observed. This indicates that indeed some of the patients showed also a longer grasping and releasing phase for the unilateral and bimanual execution while other did not. The observation of a prolonged reaching phase in patients is supported by Wu et al. who also showed a longer reaching phase of the hemiparetic arm to reach a jar. Also more error correction and les smooth movements were observed. It was suggested that patients with damage of the right hemisphere have deficits in visuospatial perception of target location. Therefore, they require more feedback control than healthy subjects. This may also explain why the bilateral execution in patients resulted in a longer duration of the reaching, lifting and putting down phases compared to the other executions, as two objects needed to be located at a marked place. In addition, the authors did not observe deficits in preplanning and forming of the handgrip [48]. This is not completely in line with our results as 2 patients, CVA3 and MS3, showed no pregrasping phase with their left hand. Moreover, this phase was not present for both hands for MS1. So, three of the five patients had deficits in preplanning of the handgrip. However, some of the patients showed no deficits in pregrasping which can be explained by the good recovery or limited impairment. We cannot make conclusions about the duration of this phase, as it was difficult to determine the start of the grasp posture. In further studies, it may be better to start with a closed fist as start position, which will simplify the determination of the beginning of the pregrasping phase. As observed in patients with spinal cord injury, the patients who did not show a pregrasping phase used a compensatory manner to grasp the block. The use of alternative joint angles in the handgrip was also determined by a study in patients with hemiparesis [61]. It was observed that some of our patients extended their wrist and passively closed the fingers around the block. Other patients kept their fingers flexed and shove their fingers over the block to open their hand. This suggests that patients with upper limb dysfunction reach and grasp sequentially, while healthy persons prepare the grasp during reaching [46]. Compared to the unilateral execution, bimanual execution resulted in an increase of the lifting phase for the less impaired arm while no difference in duration was observed for the more impaired arm. This is in line with the results of tasks duration which showed that the less impaired arm adapts to the most impaired arm [58]. In addition, retrieving was also prolonged for the most impaired hand in this condition. These results suggest that bimanual execution resulted in a longer task duration for the less impaired hand by a prolongation of the lifting phases while an increase in the duration of the retrieving phase may have resulted in a longer task duration for the most impaired hand of three patients. However, it must be stressed that this was data of only 5 patients, so these results are only an indication.

4.8 Limitations of the study

This study had several limitations. First of all, we opted for a simple measuring system, which was non-invasive and portable and made use of goniometers and torsiometers. We are aware that this system is less reliable than for instance three-dimensional analysis such as VICON which is widely used in laboratory research. However, our purpose was to apply equipment that can be used outside the laboratory setting to indicate meaningful parameters that show differences between healthy and neurologically disabled persons. These parameters can then be selected for further investigation with more sophisticated and sensitive measurement systems for example three-dimensional analysis. Our aim was not to set up a database with the normal ranges of outcome parameters. Second, the pressure sensors that were used in this study had a very small surface area, therefore it was difficult to attach them on the right position on the fingers. Moreover, two different handgrips were used to execute the tasks. Therefore, it is possible that there was a larger contact surface between the fingers and the block for certain tasks. In addition, for the tasks performed in different directions, the index finger was not used in the handgrip by some of the subjects. In the future, it is recommended to use for example objects which are covered by pressure sensors or hand gloves with pressure sensors to ensure that contact of the fingers with the block is fully measured. Third, a highly diverse patient group was recruited. This may partly explain the variability in the results that were obtained. However, this was an explorative study part which also aimed to determine which patients can participate in this study. In the future more patients can be observed. Fourth, the inter-rater reliability was not determined. For use in other laboratories and interventional studies involving multiple testers, it is necessary to determine besides the intra-rater also the inter-rater reliability. Fifth, clinical evaluation of the motor function by the Fugl-Meyer assessment method was not done. The scores of the Fugl-Meyer assessment could have been used to assess whether the patients showed movement synergies as well as to indicate whether distal and proximal motor control was similarly affected. Sixth, the test-retest design was only assessed in healthy subjects. We were mainly interested in the reliability of the application of the sensors. It was assumed when this was reliable in healthy subjects, this would also apply for the patients. And last, the mean and the range of joint angles were observed over the whole movement tasks. In the future, it is planned to investigate the joint angles and pressure of the fingers at the end of the reach movement which requires the largest range of motion or within each phase. The latter will indicate which of the phases are the most problematic in patients with upper limb dysfunction and deserves the most attention for rehabilitation research.

5 Conclusion

Kinematic and kinetic analyses are interesting tools for the quantification of the performance. The information is obtained in an objective manner and it is sensitive to minor differences or changes in the performance. Therefore, the goal of this study was to investigate objectively the distal movements of both unilateral and bilateral functional tasks in healthy and neurologically disabled persons by means of movement analysis. Our results showed that both healthy subjects and patients performed consistent over the three executions. However, more variability was observed for task duration and wrist abduction/adduction in patients. The evaluation method and the measuring system CAPTIV-L700, which was used in this study, appeared to be reliable for the outcome measures task duration, wrist abduction/adduction, wrist extension/flexion and forearm supination/pronation. Pressure sensors were not reliable due to more intra-subject variation and difficulties in placing. Therefore, it is recommended to use other force sensors in the future. For instance, objects covered by force sensors or hand gloves may result in a better reliability. These findings show that movement analysis can be used to objectively evaluate the upper limb movements while performing functional tasks. In addition, this study showed that hand dominance does not have a major influence on the movement characteristics as only the task duration of one task, wrist abduction/adduction and the pressure sensor of the thumb showed a significant difference between the right and left hand. This demonstrates that differences between the more and less impaired arm of the patients for the other outcome measures were due to the disease and not due hand dominance. Our results indicated that the inward direction required the largest range of motion. Bimanual execution was associated with a decrease in wrist extension and increase of forearm pronation, suggesting that, according to the extension synergy pattern, this execution would be easier to execute for patients. Despite that differences were observed in the descriptive data of the patients compared to the healthy subjects, no clear patterns could be observed due to high variable results. This was due to the low patient number and variation in upper limb dysfunction. So, no solid conclusions could be drawn yet. In the future, more patients divided in different groups of severity should be recruited to examine to what extent their movements differ from healthy subjects. Our study confirmed that not only the most impaired arm, but also the less impaired arm is affected shown by a longer duration of both hands compared with the healthy subjects for all the conditions of the tasks. Bimanual execution resulted for most patients, compared to the unilateral condition, in an increased task duration for both hands which was mainly due to a longer lifting phase for the less impaired hand and a prolongation of the retrieving phase for the most impaired hand. Therefore, bimanual execution does not seems to improve the performance of the more impaired limb. In fact, the arm function of the less impaired arm deteriorated.

In addition, bilateral execution resulted in a longer task duration for the patients by an increase in the reaching, lifting and putting down phase. During the execution of the task lift an object in different conditions, deficits in the formation of a handgrip were observed. As this is very important for the manipulation of objects, this deficit can be selected for further investigation with more advanced measuring systems as for instance three-dimensional analysis and sensors on the joint angles of the fingers to describe the compensatory grasp. Strength showed to be an important determinant for the ability to lift an object as high correlations were obtained with the task duration of the lifting tasks. Therefore, rehabilitation therapies should include muscle exercises for the upper limbs.

The following step of this project is to extent the analysis in more patients divided in groups with well-defined differential upper extremity dysfunction. Besides, the sensor data within each phase will be analyzed. The obtained data can then be used to describe the movement characteristics used for the execution of daily life tasks in both healthy and neurologically disabled persons. The observed differences in outcome parameters between the healthy subjects and the patients may indicate the deficits of these patients. This information can then be verified by more advanced three-dimensional analysis systems. In the future, this knowledge can be helpful in the development or the optimization of rehabilitation therapies. Individualized trainings interventions may improve upper limb function and consequently also the quality of life. Additionally, kinematics and kinetics has the potential to be used in the evaluation of the upper limb function in many neurological disorders e.g. MS, stroke, CP etc.

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