Development and validation of upper extremity kinematic movement analysis for people with stroke

Reaching and drinking from a glass

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Julge pealehakkamine on pool võitu

Well begun is half done

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ABSTRACT

Kinematic analysis is a powerful method for objective assessment of movement performance, and is increasingly employed as outcome measure after stroke. The number of studies investigating natural, goal-oriented daily tasks is however small. Likewise, little is known how the actual movement performance measured with kinematics is related to the traditional clinical assessment scales. Furthermore, only few studies investigated longitudinal changes and evaluated what these changes mean in context of an individual's functioning after stroke.

The overall aim of this thesis was to develop a method of three-dimensional movement analysis for a purposeful upper extremity task "drinking from a glass" and to evaluate the cross-sectional and longitudinal validity of the kinematic measures in relation to impairments and activity limitations in people with motor deficits after stroke.

Methods: The studies reported in the current thesis included 29 healthy individuals and 82 individuals with stroke. A standardized test protocol for the drinking task was developed and its consistency was examined. A five camera optoelectronic motion capture system with passive markers was used to measure both temporal and spatial kinematic characteristics of movement performance. The clinical outcomes used in the different studies were: Fugl-Meyer Assessment for Upper Extremity, Action Research Arm Test and ABILHAND questionnaire. The construct and concurrent validity was examined in subacute and chronic stages after stroke; the longitudinal change and responsiveness was evaluated during the first three months after stroke.

Results: The test protocol of the drinking task demonstrated a good consistency in test-retest. The explorative analysis of kinematic data revealed that the drinking task can be described with two major factors in people with stroke. One of them included predominantly measures of temporal nature (movement time, smoothness, velocity) and the other comprised primarily spatial movement pattern measures (joint angles, trunk displacement). Four kinematic measures: movement time, movement smoothness, angular velocity of the elbow and compensatory trunk displacement; demonstrated to be most effective in discriminating among individuals with moderate and mild impairment after stroke and healthy persons. Subsequently, three kinematic measures: movement smoothness, movement time and trunk displacement demonstrated strongest associations with upper extremity activity capacity after stroke, measured with Action Research Arm Test. Finally, all three kinematic measures showed to be responsive for capturing improvements in upper extremity activity during the first three months after stroke.

Conclusions and clinical implications: Three kinematic measures of the drinking task: movement smoothness, movement time and trunk displacement; demonstrated to be valid and responsive measures for characterizing the upper extremity function and to capture an improvement over time after stroke. It can be concluded, that the test protocol of the drinking task as described in this thesis is feasible for clinical studies and provides objective, valid and clinically interpretable data of an individual’s actual movement performance during the drinking task. This knowledge facilitates both clinical and movement analysis research and can be valuable in the area of bioengineering when assessment methods for new technology based devices are developed.

Keywords: kinematics, upper extremity, arm, task performance and analysis, Activities of Daily Living, outcome assessment, movement, motion analysis, stroke, rehabilitation, recovery of function

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SAMMANFATTNING PÅ SVENSKA

Tidigare studier visar att nedsatt arm- och handfunktion efter stroke förekommer initialt hos ca 70 % av de insjuknade, och hos ca 40 % kvarstår nedsättningen en längre tid. Funktionsnedsättningen i en hand eller arm påverkar förmågan att utföra dagliga aktiviteter, vilket i sin tur kan begränsa personens delaktighet i sin omgivning.

Bedömning av rörelseförmåga efter stroke utgör en viktig del av rehabilitering och ställer krav på de mätinstrument som används. Standardiserade skattningsskalor, baserade på observation är de vanligaste instrumenten som används både på klinik och i forskning för att bedöma rörelseförmågan i arm- och hand. För att mer detaljerat och objektivt bedöma arm- och handfunktion hos personer med stroke kan metoder som kinematisk rörelseanalys användas.

Kinematisk rörelseanalys beskriver rörelser i tid och rum och de vanligaste kinematiska begreppen innefattar position, hastighet och acceleration. För armen används kinematiska mått för att beskriva och analysera rörelser under en specifik uppgift eller aktivitet. Kinematisk rörelseanalys används alltmer efter stroke när behandlingseffekter eller förbättring över tid ska utvärderas i kliniska studier.

De flesta studier som har använt kinematisk rörelseanalys efter stroke har framförallt analyserat enklare armrörelser, som att peka på något eller att nå och gripa om ett föremål. Tidigare forskning har visat att kinematiska rörelsemått är beroende av uppgiftens karaktär och mål. Därmed är det viktigt att utvärdera personens rörelseförmåga i naturliga och målinriktade aktiviteter.

Det övergripande syftet med denna avhandling var att utveckla och utvärdera en metod för kinematisk rörelseanalys av en vardaglig aktivitet att ”dricka ur ett glas” hos personer med stroke. Avhandlingen omfattar fyra delstudier. I den första studien utvecklades och utvärderades kinematisk rörelseanalys av aktiviteten dricka hos friska personer. Syftet med den andra studien var att identifiera de mest kliniskt relevanta kinematiska rörelsemåtten, för att kvantifiera (mäta med siffror) och beskriva rörelser hos personer med stroke. I den tredje studien undersöktes hur väl de kinematiska rörelsemåtten avspeglar personens funktionsnedsättning och aktivitetsbegränsning bedömt med kliniska instrument. I den fjärde studien utvärderades hur känsliga de kinematiska rörelsemåtten är för förändring i armens aktivitets kapacitet efter stroke.

Metod: Totalt ingick i de fyra delstudierna 82 personer med stroke samt 29 friska personer. Ett standardiserat testprotokoll för kinematisk rörelseanalys av aktiviteten att ”dricka ur ett glas” utvecklades och dess repeterbarhet testades. Ett optoelektroniskt rörelseanalyssystem med fem hög-hastighetskameror användes. Kamerorna registrerade rörelsedata från självreflekterande markörer som var placerades på personens kropp och på dricksglaset.

De huvudsakliga kinematiska rörelsemåtten som ingick i analysen var: tid, maximal hastighet, rörelsestrategi, jämnhet/smidighet i rörelsen, ledvinklar och koordination. De kliniska bedömningsinstrumenten som användes i delstudierna var: Fugl-Meyers bedömning av sensomotorisk funktion i övre extremiteten (FMA-UE), Action Research Arm Test (ARAT) samt frågeformulär ABILHAND.

Resultat: Testprotokollet som utvecklades i den första studien för aktiviteten dricka visade god repeterbarhet i test-retest. Den andra delstudien visade att variansen i kinematikdata från aktiviteten dricka hos personer med stroke till största delen representerades av två huvuddimensioner. En av dem innefattade huvudsakligen temporala mått (tid, hastighet, jämnhet/smidighet) och den andra spatiala mått (ledvinklar, kompensatorisk bålrörelse). Fyra kinematiska rörelsemått (tid att utföra hela aktiviteten, jämnhet/smidighet i rörelser, vinkelhastighet i armbågsled och kompensatorisk bålrörelse) visade sig vara mest effektiva för att differentiera skillnaderna i armfunktion hos friska och personer med stroke.

I den tredje delstudien visades ett starkt samband mellan tre kinematiska rörelsemått (tid att utföra hela aktiviteten, jämnhet/smidighet i rörelsen, och kompensatorisk bålrörelse) och aktivitets kapacitet mätt med Action Research Arm Test (ARAT).

Den sista delstudien visade att de tre kinematiska rörelsemått identifierar väl personer med reell klinisk förbättring i armrörelser. Alla tre kinematiska måtten var känsliga för förändring i aktivitetsförmåga efter stroke under de tre första månaderna efter stroke.

Slutsats och klinisk betydelse: Resultatet från denna avhandling visar att kinematisk rörelseanalys av en målinriktad daglig aktivitet att ”dricka ur ett glas” är användbart för att beskriva och analysera rörelser hos personer med stroke. De kinematiska mått som visats vara lämpligast för att karakterisera och kvantifiera funktion och aktivitet i övre extremiteten efter stroke var: tid för att utföra hela aktiviteten, jämnhet/smidighet i rörelsen, och kompensatorisk bålrörelse. Dessa tre kinematiska mått kan rekommenderas för att objektivt bedöma rörelseförmågan i övre extremiteten efter stroke; de korrelerar väl med klinisk bedömning av armfunktion och aktivitet och de är känsliga för förändring över tid efter stroke. Dessutom visar resultat presenterat i denna avhandling att både temporala och spatiala aspekter av en rörelse/aktivitet är betydelsefulla när armfunktionen analyseras hos personer med stroke.

De tre kinematiska måtten kan med fördel användas till exempel i kliniska studier eller i klinisk praxis för att utvärdera en specifik behandling eller för att planera rehabiliteringsinsatser efter stroke.

LIST OF PAPERS

This thesis is based on the following studies, referred to in the text by their Roman numerals. Reprints are made with permission from the publishers.

I. Alt Murphy M, Sunnerhagen KS, Johnels B, Willén C. Three-dimensional kinematic motion analysis of a daily activity drinking from a glass: a pilot study. *Journal of Neuroengineering and Rehabilitation 2006; 3:18.*

II. Alt Murphy M, Willén C, Sunnerhagen KS. Kinematic variables quantifying upper-extremity performance after stroke during reaching and drinking from a glass. *Neurorehabilitation and Neural Repair 2011; 25(1):71-80.*

III. Alt Murphy M, Willén C, Sunnerhagen KS. Movement kinematics during a drinking task are associated with the activity capacity level after stroke. *Neurorehabilitation and Neural Repair 2012; 26(9):1106-1115.*

IV. Alt Murphy M, Willén C, Sunnerhagen KS. Responsiveness of upper extremity kinematic measures and clinical improvement during the first three months after stroke. *Neurorehabilitation and Neural Repair 2013; 27(9): 844-853.*

CONTENT

ABBREVIATIONS

ARAT	Action Research Arm Test
ADL	Activities of Daily Living
AUC	Area Under the Curve
CI	Confidence Interval
ES	Effect Size
FMA	Fugl-Meyer Assessment, FMA-UE for Upper Extremity
ICC	Intraclass Correlation Coefficient
ICF	International Classification of Functioning, Disability and Health
IJC	Interjoint Coordination
LOA	Limits of Agreement
MAS	Modified Ashworth Scale
MCID	Minimal Clinically Important Change
M-MAS UAS	Modified Motor Assessment Scale, Uppsala Akademiska Sjukhus
MT	Movement Time
NMU	Number of Movement Units, MU for Movement Units
PAVE	Peak angular velocity of the elbow joint
PCA	Principle Component Analysis
PV	Peak velocity
ROC	Receiver Operating Characteristic
ROM	Range of Motion
SALGOT	Stroke Arm Longitudinal study at Gothenburg University
SPSS	Statistical Packages for Social Sciences
SRM	Standardized Response Mean
SU	Sahlgrenska University Hospital
T2PV	Time to Peak Velocity
TD	Trunk Displacement
TMT	Total Movement Time
WHO	World Health Organization
WCPT	World Confederation for Physical Therapy

PREFACE

In recent years there has been a tremendous expansion of research in the field of physiotherapy. The landscape of research in physiotherapy is also changing as interaction with adjacent research fields is growing. From the clinical side, increased demand for "evidence-based practice" and constant need to determine which treatment is most effective are further pushing forward clinical outcome research.

In my clinical practice, I have experienced a lack of specific outcome measures for the upper extremities after stroke. Often the arm function is assessed as part of a combined assessment scale that includes items from many different functioning areas. This makes the specific assessment difficult and diminishes the possibility to evaluate the progress in arm function. In addition, the outcome measures used in physical therapy practice and research for upper extremities are often observational rating scales and the disadvantage of the ordinal scaling and subjectivity in scoring cannot be denied. Parallel to these clinical scales, objective and quantitative measures of upper extremity function can be used to obtain detailed and specific information of movement performance and quality during a task. These measures, on the other hand, require more technical equipment and knowledge, and are not easily available in clinical settings. Kinematic analysis, however, can give us a deeper understanding of the underlying mechanisms of movement control, for example during a purposeful natural task. In addition, increased knowledge regarding the underlying construct and measurement properties of different outcome measures is essential both for research and clinical practice.

This thesis presents four studies where the upper extremity movement performance in healthy people and in people after stroke was measured with an objective kinematic movement analysis technique. The upper extremity performance was evaluated during a daily task - the drinking task. The most sensitive and clinically relevant kinematic measures for people with stroke were identified and the sensitivity to change over time (responsiveness) was evaluated for key measures of kinematic analysis.

This theses is highly influenced by the "physiotherapist's glasses" I am wearing but also by the experiences and inputs I have received from the multiprofessional clinical and research groups I have worked with during the past years. I hope that this thesis will reduce the gap between different research areas and in the long run help clinicians as well as individuals with stroke to accomplish their goals. Finally, I would like to cite Jill Bolte Taylor who wrote a fascinating book "My stroke of insight. A brain scientist's personal journey"[1] to illustrate an important and central point of stroke rehabilitation.

For a successful recovery, it was important that we focus on my ability, not on my disability.

Jill Bolte Taylor, "My stroke of insight", p.117

INTRODUCTION

Stroke

About 25 000 to 30 000 individuals suffer from acute stroke each year in Sweden. The mean age for stroke onset in Sweden is 76 years (73 years for men and 78 years for women) which means that men are overrepresented in the group of people <65 years and women are overrepresented in the age groups of 85 years and older.[2]

With an aging population and an improved survival rate,[3] the prevalence of stroke will be expected to increase in the future,[4] and the prevention of stroke related disabilities will become even more important.[3] With this in mind, about 1/3 of the survivors will be dependent on others for their personal activities of daily living (primary ADL) and remain significantly disabled after 6-12 months.[2] And indeed, stroke is accounted as one of the most common neurological disability among adults in Sweden.[2]

Stroke is therefore a major and increasing health care problem and accounts for major economic challenge for the society. Stroke, however is not just affecting the society with its statistics and an economical load. The consequences of stroke are first and foremost affecting the individual suffering from stroke and his or her environment including family and friends. For example, a person's ability to walk or perform common tasks can be significantly compromised after a stroke. Similarly, the level of independence and ability to participate in the society can be drastically changed which in turn affects a person's quality of life.[5]

One of the most widely described impairments caused by stroke is the motor function. Impaired motor function and movement control on one side of the body has been reported to be present in approximately 80% of patients.[6] These sensorimotor deficits will limit the individual's ability to perform different tasks in their daily life and the risk that it may restrict the individual's possibility to participate in a society is high.

Theoretical framework

ICF – International Classification of Functioning, Disability and Health

The integrated model of International Classification of Functioning, Disability and Health (ICF) [7], approved by the World Health Organization (WHO) in 2001, has had a great influence on the field of rehabilitation.[8,9] With its multi-perspective bio-psychosocial approach, the model provides a wider understanding of human functioning and disability and forces health professionals to look further than the usual perspective, which has traditionally lain in the domain of body function and structures.

The components of ICF can be used to indicate functioning or disability on three different levels: body function or body structure indicates what are the prerequisites for someone's functioning, activity represents what someone can do, and participation describes what someone does in the actual context in which they live. The domains of activity and participation can be divided into capacity (an individual's ability to execute a task or activity, for example in a standardized environment) or performance (what an individual does in his or her actual environment). In the model, the consequences of a disorder or a disease on the individual person are evaluated in the context of their social and physical environment and personal resources. The structure of ICF and its components along with examples of typical functioning areas and contextual factors are presented in Figure 1.

The ICF is an excellent tool for visualizing the rehabilitation process and can successfully be used in selection of appropriate assessment, goal setting and intervention planning.[10] Although the components of ICF are related, they represent different aspects of functioning, and therefore assessments on each domain are recommended in order to fully understand the impact of disability.[10,11]

Rehabilitation

Rehabilitation can be defined as the health strategy that aims to enable people with health conditions experiencing, or likely to experience disability, to achieve and maintain optimal functioning in interaction with the environment.[8,12]

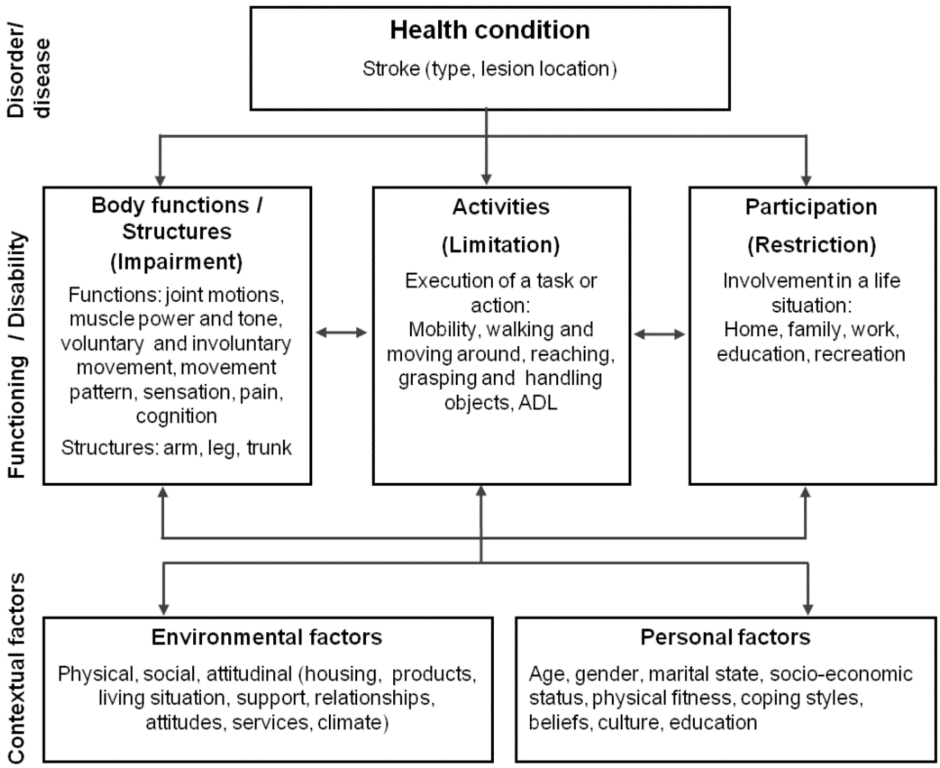

Figure 1. International Classification of Functioning, Disability and Health (ICF) along with examples of typical functioning areas and contextual factors.

The scientific field of rehabilitation is broad and multiprofessional in its nature.[8] The academic development in the field of rehabilitation medicine has been advancing rapidly during the last decades. This advancement is to a large extent influenced by interdisciplinary research efforts from many different fields incorporating professionals from medical care, physiotherapy, occupational therapy, psychology, speech therapy, social sciences and other health sciences.[13]

The specialty of rehabilitation medicine applies and integrates the bio-psychosocial model of functioning, disability and health (ICF) through a multi-professional approach. Rehabilitation is an active, educational problem solving process focused on a patient's behavior (disability) in his or her environment. The multidisciplinary team, individual goal settings and high patient (and family) engagement are all core elements of rehabilitation strongly associated with good outcome.[14]

Rehabilitation after stroke is a complex process. It is a major challenge both for therapists and patients as the consequences of stroke influencing a person's daily life will be confronted in many ways. The ultimate goal of stroke rehabilitation is to enable the patient to regain the highest possible degree of physical and psychological performance in order to achieve functional independence necessary for returning home so that the participation in their community life can be attained.[15]

This description illustrates the width of rehabilitation as a discipline and shows that the selection of appropriate assessment tools is crucial for adequate evaluation, and that this selection will consequently influence the entire rehabilitation process, including discharge planning and selection of interventions.

Physiotherapy and motor control theories

Over the last decades, the development of scientific knowledge of physiotherapy has advanced significantly. The basic concepts of physiotherapy - movement and functioning - along with a clear definition of physiotherapy, have been defined by the World Confederation for Physical Therapy (WCPT).[16] Also the development and increased use of the ICF model have had a great impact on the physiotherapy as a discipline. This theoretical framework is frequently applied to the physiotherapy practice, education and research.

Physiotherapy is closely related to many other areas and disciplines, for example motor learning and control, movement science, sports medicine, rehabilitation and psychology. Many different theories and approaches coexist and development of a theoretical model that explicitly explains the core concepts of physiotherapy is still an ongoing process.

Shumway-Cook and Woollacott[17] have had a major impact in bringing translational research from the motor control area to physiotherapy clinical practice. They emphasize that movement emerges from a close interaction between the individual, the task, and the environment in which the task is being carried out (Figure 2). The individual's movement capacity that meets the constraints of the task and environment, determines his or hers functional capability. Within the individual, movement emerges from the interaction of multiple processes, such as control of the motor action, perception and cognition. Factors within the task incorporate the organization of functional movements (taxonomy) where the demands on the mobility, stability and manipulation can be described. Finally, the movement itself is also constrained by the factors within the environment that regulate the movement (regulatory factors, e.g. size, shape, weight of a cup to be picked up) and the factors that may affect the movement performance without direct shaping (non-regulatory factors, background noise, other distractions).

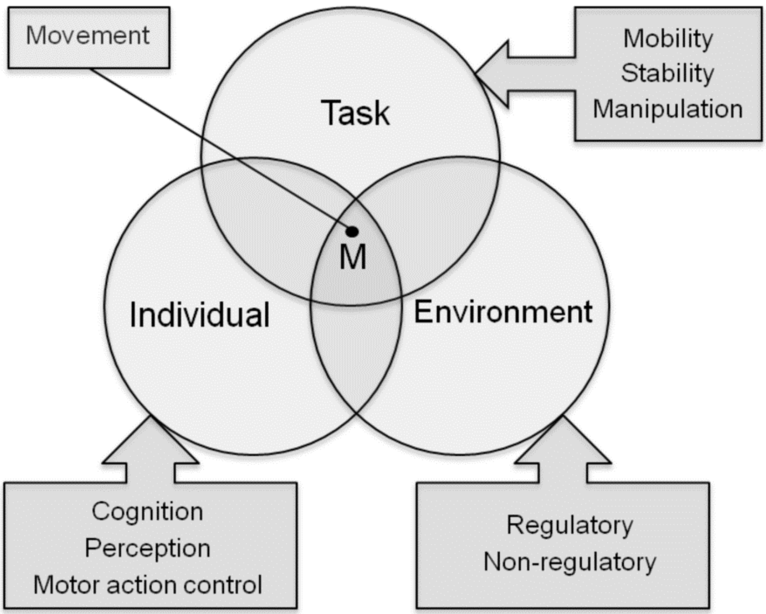

Figure 2. Movement emerging from interaction between the individual, the task and the environment. Adapted from Shumway-Cook A, Woollacott MH. Motor control : translating research into clinical practice 2012.

Along with development of motor control theories a change of paradigms can also be seen in physiotherapy clinical practice, in which a shift from earlier therapies, focusing primarily on neurofacilitation approaches, to task-oriented approaches can be seen.[17] In the future, the current theoretical models and approaches will most likely expand even further and future theories will probably emphasize the individual's perspective as it is perceived by them even more. A more person-centered approach would add an extra dimension to the existing models and give an individual a more active role in their rehabilitation process.

Recovery and compensation

Recovery is probably one of the most central issues in stroke rehabilitation. It has been suggested that recovery after stroke is a combination of spontaneous and learning dependent processes and it may be subsumed within three general mechanisms: restitution, substitution and compensation.[6,14,18] The restitution mechanism includes restoring the functionality of a damaged non-infracted penumbral area and is believed to have a time window from several hours to first days after stroke. The substitution mechanism involves reorganization of partly spared neural networks to relearn lost functions and is often referred to as neural or brain plasticity. Finally, the compensation mechanism, during which improvement occurs through changed behavior. All these mechanisms of recovery are probably responsible for the functional improvement observed after stroke and can to a large extent explain the observed non-linear pattern of recovery.[15]

It has been recognized that improvements of motor skills during the early stages of stroke rehabilitation depend mainly on spontaneous reparative process and reorganization of neural mechanisms and that long-term functional improvements are mainly accounted for by compensational adaptations.[19] It is also clear that the final recovery is to a large extent dependent on the inputs and demands given to the motor control system by the person or environment.[19]

Some inconsistency exists, however, when the term recovery is defined in the literature. Generally, recovery is often used to describe the overall improvement toward the functioning level that the person had prior stroke and in these cases no distinction is generally made between the true recovery and compensation. The clarification between recovery and compensation is however important from rehabilitation perspective so that specific intervention could be directed toward the specific motor problem or activity limitation either with the aim to restore the earlier ability or to encourage an alternative way to accomplish the task.[17,19] Clear definitions as suggested by Levin et al. (Table 1), along with the use of outcome measures with sufficient precision at impairment and activity limitation levels would assist in the distinction between compensation from the true recovery.[19]

Table 1. Definitions of motor recovery and compensation at body function and activity level.

ICF level	Recovery	Compensation
Body Functions	Restoring the ability to perform a movement in the same manner as it was performed before injury (reappearance of premorbid movement patterns: voluntary joint range of motion, coordination, reduction of trunk displacement during reaching etc.)	Performing an old movement in a new manner (using an alternative movement pattern: using different degrees of freedom, co-activation, delays in movement timing, excessive trunk displacement or shoulder elevation and diminished elbow extension in reaching, alternative finger positions in grasping etc.)
Activity	Successful task accomplishment using body parts typically used by non-disabled individuals (using two hands in bilateral tasks, grasps with appropriate fingers)	Successful task accomplishment using alternative body parts (opening a package of chips using one hand and the mouth instead of two hands)

Adapted from Levin et al. 2009

Arm function and activity after stroke

The most widely recognized impairment after stroke is motor impairment, which restricts voluntary, well coordinated, and effective movements on one side of the body.[6] Muscle weakness (hemiparesis) is recognized as the major deficit contributing to the motor impairment. Other associated motor disorders, such as spasticity, muscle stiffness and reduced muscle length, coordination and timing of movements, presence of abnormal movement patterns may also influence the motor function. In addition, sensory impairments, perceptual deficits and cognitive difficulties after stroke may limit the use of arm and hand in daily life activities.[17]

Reduced upper extremity function after stroke has in previous studies been reported in approximately 70% of patients in acute phase.[20,21] A more recent cohort study from a stroke unit in Sweden, reported impaired upper extremity function 72 hours after first ever stroke to be present in 48% of patients in a non-selected population.[22] The authors speculate that this lower prevalence of upper extremity impairment in the acute stage can be caused by the improved primary and secondary prevention of stroke but they recognize as well that the differences in inclusion criteria and assessment methods could have influenced the outcome.[22]

About 40% of stroke survivors continue to show impaired upper extremity function even 3-6 months afterwards and more than half of the patients who had undergone rehabilitation during their recovery, reported that the limited upper extremity use in daily life was a major problem 4 years after stroke.[23,24]

Among other associated impairments influencing upper extremity motor function, spasticity has been reported to vary between 20% and 30% after first stroke and among those with hemiparesis, the prevalence varies between 30% and 40%.[25] It must be noted that almost all patients with spasticity exhibit hemiparesis, but all patients with hemiparesis don't necessarily have spasticity.[25] Approximately 50% of people with stroke experience sensory impairment, especially of tactile and proprioceptive discriminations. [26] Shoulder pain on the affected side is one complication after stroke and has been reported to be present in approximately 20% of patients.[23,24,27]

Recovery

Findings from longitudinal studies indicate that recovery of upper extremity motor function follows a nonlinear pattern and that the main improvement occurs within the first months after stroke.[15,21,24,28,29] Initial severity of paresis and time after stroke seem to be the most important predictors for regaining arm motor function.[30] One of the largest studies with a non-selected population where the upper extremity activities were evaluated with Barthel Index (Copenhagen study) showed that 80% of the patients reached their plateau or best possible activity level within the first 3 months after stroke.[20] A distinct difference in the time course of recovery between patients with mild and severe paresis could be seen. Patients with initial mild paresis tend to recover fast and patients with severe paresis show slower speed of recovery.[20] Another non-selected study with longer follow-up times demonstrated that at least in 13% of patients, significant functional improvement could be observed also between 3 and 6 months after stroke. Several studies, conducted with selected populations at rehabilitation units, have shown as well that in some patients, the improvements continued for longer time periods. [23,31]

Assessment

In order to evaluate recovery or determine the efficacy of a treatment, valid, reliable and responsive outcome measures are essential and required during all stages of stroke rehabilitation.[32] The essential measurement properties for standardized outcome measures are validity, reliability and responsiveness.[33] An important characteristic of a measurement instrument that is not considered as a measurement property, but more like a qualitative meaning of a score or change in a score, is interpretability. Interpretability shows the degree to which it is clear what the scores on an instrument mean in a clinical (or research) context.[33]

An outcome measure can be used for different purposes: to discriminate between people with different impairment or activity levels (discriminative measures), to predict future outcome (predictive measures), or to evaluate longitudinal changes (evaluative measures).[34] In selection of outcome measures, natural history of stroke and stroke severity must also be considered.[34] For example, an outcome measure suitable for acute care may be too easy or narrow for the patients in the chronic stages of stroke when aspects of activity performance and participation will become more central. Similarly, different aspects of function and activity can be in focus for patients with severe or mild impairments. For example, the level of independence during activities of daily living may be the target for patients with severe hemiparesis. On the contrary, when the ability to perform different tasks has been achieved, the aspects of precision and movement quality are of greater value to assess.

In selection of assessment tools, different methods for acquiring data must also be considered. A person's motor performance can be assessed using an observational rating scale or a measurement device, such as stopwatch, dynamometer or kinematic movement analysis. Questionnaires can be used to gather information on individuals' functioning by different means including patient or professional reported measures.[34] Finally, the data acquired can be differentiated based on the level of measurement: nominal, ordinal, interval or ratio; which determines the mathematical manipulations and statistical tests that are appropriate to use for data analyses.

Upper extremity function after stroke in clinical research and practice is generally assessed with observational rating scales, such as the Fugl-Meyer Assessment, Action Research Arm Test, Wolf Motor Function Test, Frenchay Arm Test, Motor Assessment Scale.[35-38] These clinical scales are valid and reliable for determining the impairment or activity limitation levels and for measuring gross changes in motor performance, but may be less sensitive to smaller and more specific changes. [39] Neither is the qualitative detailed information of movement performance, including the specific movement patterns and motor compensation strategies, captured with these clinical measures.[19] Another aspect that must be highlighted is the ordinal-level scoring that is common for many rating scales, since it is dependent on the observer and the pre-set scoring levels.

Clearly, selection of an appropriate outcome measure is crucial and has a major impact on the interpretation and implication of the study results. Similarly the outcomes used in clinical practice influence the clinical decision making process and interact closely with treatment planning. This topic has recently been highlighted in several reviews which provide some guidance to researchers and clinicians.[10,11,40,41] The use of the ICF model has been advocated by many authors to optimize the selection of outcome measures for clinical research and practice.[34] For example, in the area of upper extremity rehabilitation after stroke, the outcome measures with adequate psychometric properties and clinical relevance have been identified for robot-assisted exercise trials[11] and for measures reflecting the "real-life" functioning.[40] In these reviews, the Fugl-Meyer Assessment (FMA), Action Research Arm Test (ARAT) and ABILHAND were identified, among others, as scientifically appropriate and clinically relevant stroke specific scales.

Kinematic movement analysis of upper extremity

Kinematics describes movements of the body through space and time without consideration of the cause of motion and forces involved.[42] The term kinematic is the English version of cinématique which A.M.Ampere constructed from the Greek word *ki´nēma* (movement, motion). And indeed, kinematics has historically a strong connection to the cinematography. The earliest kinematic studies on human walking were performed in the 1870 in Paris and in California and the first major studies of gait analysis were undertaken during 1940s and 1950s also in California.[42-44] In the 1970s and 1980s measurement systems based on the television cameras, which were linked directly into computers (optoelectronic systems) were first developed.[42,43] This was also a starting point for wider use of gait analysis in clinical application. During the last 30 years, the number of gait laboratories has been increasing drastically in many countries.

What about the kinematic analysis of arm movements? In the 1990s the kinematic movement analysis was "moving upwards", as it was described by the Rau et al[45], but the transfer of the knowledge and experience gained in lower extremity movement analysis to the analysis of upper extremities have turned out to be difficult. The main reason for this is the larger complexity, variety and range of arm movements. The upper extremity is used in versatile daily activities; we reach, grasp and manipulate with different objects and tools, we shake hands and gesticulate and we perform precise fine motor tasks. Also, the need to describe movement in different planes in three-dimensional space is larger for upper extremity tasks compared to gait analysis. Contrary to gait analysis, normalization and averaging based on the cyclic nature of movement is generally not applicable to the upper extremities.[45] The variability of upper extremity tasks as well makes the comparison between different tasks more complicated. The complexity of arm movements is still a challenge and clinical routines for three-dimensional analysis in upper extremities are not fully established.[45]

Kinematic movement analysis can be used in many different areas that may answer different research questions and use different measures to describe and to quantify human movements. Some of the application areas, purposes of the use and typical measurement variables are listed in the Figure 3. Clearly, no single method of analysis is suitable for such a wide range of uses and number of different methodologies have been developed and used.[42] It is also understandable that in clinical application the system set-up, data analysis and studied tasks need to be relatively manageable in terms of costs, complexity, space and time.

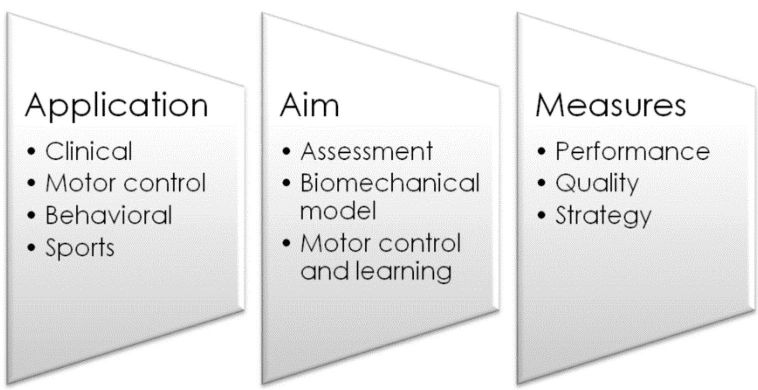

Figure 3. Different application areas, aims and common measurement areas for kinematic movement analysis of upper extremity.

Three-dimensional imaging measurement techniques, including optoelectronic systems, have been widely used by many laboratories and have turned out to be a powerful tool for a quantitative assessment of movement in all degrees of freedom.[45] An optoelectronic system comprises a set of high speed cameras which are synchronized and connected to a computer for real time analysis of the capture data. To capture movement data, retroreflective circular markers are fixed on the body. The cameras emit short infrared light pulses that hit the markers, which reflect the light back into the cameras and are then seen as light sources by the cameras. The marker positions based on the size and center point coordinates are calculated in real-time in the camera and then transferred to the computer software. Then the markers are identified and labeled using tracking software, and the three dimensional marker positions are calculated using trigonometry and subsequently saved in the computer file. In kinematic movement analysis of the upper extremity, the displacements of body segments, joint angles, tangential and angular velocities and accelerations are commonly recorded.

Prior to measurement, the system is calibrated to the measurement volume using a fixed reference structure which defines the origin and orientation of the global coordinate system and a movable calibration object (wand). The wand is moved in the measurement volume to generate data to determine the locations and orientations of the cameras. When a person moves inside the measurement volume, the marker positions on the person's body are calculated, as long as they are visible to at least two cameras. Data are collected at series of time intervals known as frames that correspond to frequencies. The most common data collection frame rates used in clinical movement analysis varies between 50 to 240Hz.

The optoelectronic systems have in general a high resolution (ability to measure small changes in marker position), high precision (low system noise) and high accuracy (high concurrence between the actual position of a marker and the calculated position by the system).[42,46] High measurement accuracy is achieved at higher frequencies and it is dependent on the size of the markers, measurement distance and the camera field of view.[42,46] In modern optoelectronic systems the accuracy is relatively high and has been reported to be smaller than 1 mm for a typical gait analysis set-up.[42] In upper extremity analysis, the measurement volume is generally smaller and the cameras are closer, which means that the measurement error dependent on the system can almost be neglected.

However, even when the accuracy is high for position data, it must be noted that the measurement noise increases when mathematical differentiation of the position data to linear and angular velocity is performed. This noise is further increased when differentiation to determine acceleration is required. To avoid this problem, low-pass filtering is used to smooth the position data before differentiation. Thus, kinematic systems are excellent at measuring position, but less accurate at determining acceleration.[42,46]

Another cause of measurement errors is the possible shift between the marker attached to the skin and the underlying bone.[42,46] This problem can be diminished when the markers are attached on the bony landmarks of the body on the locations where the skin movement is minimal. When the marker triads fixed to a limb segment with an elastic strap are used, the possible movement caused by the skin, soft tissue and muscle contraction underneath can be problematic and cause measurement errors.[42,46]

There are two main approaches to positioning the markers on the body; directly to the skin separately over bony anatomical landmark (single marker-based model), as a set of at least three markers per segment (cluster-based model) or a mix of both of them. All methods have advantages and disadvantages and allow different mathematical calculations for limb movements. For example, in the single marker-model the kinematic structure is simplified and the calculation of rotation of the body segments is usually limited.[47]

Kinematic movement analysis after stroke

In contrast to gait analysis, which is well established and applied both in clinical research and in individual patient assessment, the upper extremity analysis has primarily been used for research purposes. Early kinematic studies in people with stroke were predominantly descriptive, establishing the method and evaluating different conditions and movement constraints during reaching. During the last years, kinematic analysis of upper extremity performance has also been used for evaluation of effects of different therapeutic interventions[48-53] and in longitudinal studies examining the motor recovery after stroke. [54,55] Also the sample sizes have been steadily increasing concurrently with technical development and increased knowledge in the area. Thus, as the cost for equipment decreases and the standard ready-programmed applications for the upper extremity become available, the use of kinematic movement analysis in clinical settings could become more realistic. To illustrate this development over the years in kinematic studies, a selection of the key studies investigating upper extremity movements is provided in the Appendix.

Many studies using kinematic analysis of upper extremities involve a reaching movement to a target at different locations: close, far, low, high, ipsilateral, contralateral or midline space. The reaching movement is often carried out under different conditions: with or without trunk constraint, vision or accuracy demand; at self-paced speed or fast; constrained to horizontal plane; bilateral or unilateral; with or without an actual object (Appendix). Some studies also include grasping of an object, typically a cone or a can[56-59], lifting an object[49] or transport of an object.[60] Only few studies have used a task that is more "natural" and similar to those performed in everyday life; like moving the hand to the mouth[61] or reaching for a cup to drink a sip of water[62,63]; in these studies only the reaching phase was used for analysis. Also in studies that evaluate the effect of presence or absence of an object or the effect of specific characteristics of the object on the reaching performance, usually only the reaching phase to the object has been analyzed.[62,64-66]

The number of kinematic measures that can be obtained and calculated from movement capture data is very large. A variety of different measures have been reported and for today, there is no consensus among researches which kinematic parameters are to be preferred for evaluation of upper extremity motor performance in people with stroke. Measures of movement time and velocity, smoothness (number of movement units, hand path ratio, hand path), accuracy (movement error), angular movement of shoulder and elbow joints, trunk displacement, interjoint coordination of shoulder and elbow joint and movement strategy (time to peak velocity, acceleration) have frequently been reported. A majority of these measures have shown to be able to discriminate between affected and non-affected reaching in previous studies.[57,58,67-73]

Correlation between kinematic measures and clinical stroke severity in reaching has been reported in several studies [57,71,74] but the reliability[59,75,76] and responsiveness[61,77] of kinematic measures have been less investigated after stroke. Stroke severity, measured with the Fugl-Meyer Assessment (FMA), has been reported to correlate well with trunk displacement [56,57,68], elbow extension and shoulder flexion [68] during reaching. Also presence of spasticity have shown relatively high correlations with movement time and trunk displacement in reaching.[68]

The kinematic variables of movement time, smoothness and trunk displacement in the reach-to grasp tasks, have been reported to be stable and reliable measures of motor performance in people with stroke[59] and cerebral palsy.[78] The responsiveness of kinematic measures in upper extremity tasks has, however, only been addressed in two earlier studies.[61,76] In these studies, the responsiveness was reported to be high for the movement duration and smoothness in reaching and in hand-to-mouth tasks after stroke.[61,76]

The knowledge gained from previous studies is essential and answers many important questions. On the other hand, researchers need to enlarge the spectrum of tasks studied and focus as well on the natural purposeful activities from people's everyday life.[39] These are the tasks that are highly prioritized by the patients and clinicians and these are the tasks that a person with impairments wants to improve.

There is also an urgent need to find valid and psychometrically sound objective measures for evaluation of the recovery process or treatment effect after a stroke. Technology-based objective assessments, such as kinematics, can successfully be used as complementary assessments to the current clinical outcome measures in order to better understand the underlying mechanisms of upper extremity performance after stroke.[39] The use of sound and effective outcome measures can support the development of appropriate care plans, allow the clinicians to quantify observations and compare patient status between examination periods, compare patient outcomes between settings and enhance the methodological quality of clinical trials etc. In addition, a rapid development of technology-based devices is emerging in the area of neurorehabilitation, which emphasis further the need to evaluate the effectiveness of these devices. In the future, a close collaboration is needed between researchers, clinicians and engineers in order to develop future assessments and treatments with a user-centered approach.

AIM

The overall aim of this thesis was to develop a method for three-dimensional movement analysis of a purposeful upper extremity task - drinking from a glass - and to evaluate the cross-sectional and longitudinal validity of the kinematic measures in relation to impairments and activity limitations in people with motor deficits after stroke.

The specific aims of the studies were:

Paper I

To develop a protocol, test the consistency of that protocol and describe three-dimensional kinematic movement analysis of a daily activity - drinking from a glass - in healthy individuals.

Paper II

To identify a set of clinically useful and discriminative kinematic measures to quantify upper extremity motor performance after stroke during reaching and drinking from a glass.

Paper III

To determine the relationships between the objective kinematic measures of the drinking task and the impairments and activity limitations after stroke assessed with traditional clinical instruments.

Paper IV

To evaluate the responsiveness and expected change in kinematic measures for the drinking task in relation to the clinical improvement during the first three months after stroke.

METHODS

Study design and population

An overview of the study designs, main analysis methods along with inclusion and exclusion criteria for participants included in paper I-IV is displayed in Table 2. All studies were conducted at the Sahlgrenska University Hospital (SU), Gothenburg, Sweden, and all participants with stroke were current or former patients at SU or recruited through a patient organization and living in the larger Gothenburg area.

An overall study population comprised 82 individuals with stroke and 29 healthy participants. A detailed description of study samples is displayed in Figure 4. Study I and II had separate samples. Participants in Study III and IV were extracted from the SALGOT cohort (Stroke Arm Longitudinal Study at Gothenburg University). Study III included 30 individuals and Study IV included 51. The selection procedures are described in detail in Paper II and IV.[79,80]

A summary of demographic and clinical characteristics of participants included in Paper I-IV is presented in Table 3. In Study II, the participants in the stroke group were divided further into two subgroups based on the FMA-UE scores: moderate (score 39-57) and mild (score 58-64). And in Study IV, the participants were divided further into two subgroups based on the change in ARAT scores between baseline and follow-up (3 months post-stroke). The subjects who showed less than 6 points improvements on the ARAT (<10% of the total score) comprised a subgroup 1 and the subjects demonstrating improvements equal or more than 6 points (>10%) comprised a subgroup 2. Thus, subgroup 2 included only subjects who demonstrated a real clinical improvement in upper extremity function based on the change in ARAT.[81]

Table 2. Overview of the study design, samples, inclusion and exclusion criteria in paper I-IV.

	Paper I	Paper II	Paper III	Paper IV
Design	Cross-sectional	Cross-sectional	Cross-sectional	Longitudinal Prospective
Analysis	Descriptive	Explorative (PCA); Analysis of differences	Analysis of relationships	Analysis of change; Interpretability
Measurement properties	Test-retest	Construct validity (dimensionality, discriminative)	Criterion validity (concurrent)	Responsiveness
Subjects	Healthy (n=20)	Stroke, chronic (n=19) Healthy (n=19)	Stroke, subacute and chronic (n=30)	Stroke, acute and subacute (n=51)
Recruitment	Convenient sample	Convenient sample	SALGOT-study (consecutive inclusion from stroke unit 3 days post-stroke)	
Inclusion criteria	Right hand dominance; in "good health" by their own opinion, age 30 or older	First ever stroke at least 3 months earlier, ability to perform drinking task with their affected arm, age 18 or older Healthy, as Paper I	First ever stroke; upper extremity sensorimotor impairment; ability to perform drinking task with their affected arm, age 18 or older Upper extremity impairment at day 3 post-stroke (FMA-UE≤64)	Upper extremity impairment at day 3 post-stroke (ARAT<57)
Exclusion criteria	Musculo-skeletal or neuro-logical problems affecting the arm function	Other non-stroke related musculoskeletal or neurological problems affecting the arm function Healthy; as Paper I	Other upper-extremity condition or severe multi-impairment or diminished physical condition prior to the stroke that limits the functional use of the affected arm; short life expectancy due to other illness (cardiac disease, malignancy); not Swedish speaking	

Abbreviations: PCA, Principal Component Analysis; SALGOT, Stroke Arm Longitudinal Study at Gothenburg University; FMA-UE, Fugl-Meyer Assessment for Upper Extremity; ARAT, Action Research Arm Test

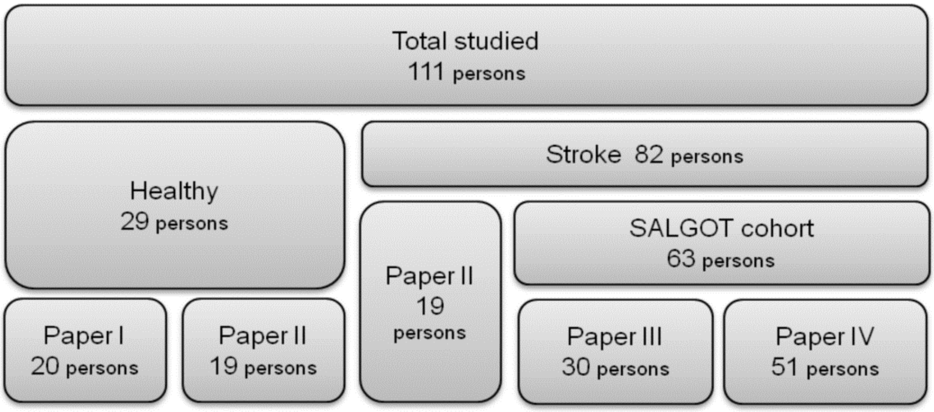

Figure 4. Study population and number of participants included in Paper I-IV. Note that, 18 participants from the SALGOT cohort were included both in paper III and IV.

Table 3. Demographic data and clinical characteristics of the participants in all four studies.

	Paper I	Paper II	Paper III	Paper IV
Subjects, n				
Healthy	20	19	NA	NA
Stroke	NA	19	30	51
Age, mean±SD				
Healthy	48±11.5	57±10.1	NA	NA
Stroke	NA	61±11.0	66±12.8	65±11.8
Male/Female, n				
Healthy	9/11	10/9	NA	NA
Stroke	NA	13/6	15/15	31/20
Time post-stroke, mean±SD	NA	19±16.4 months	2.5±2.4 months	9.6 days at baseline
Infarct/Hemorrhage, n	NA	14/5	18/12	44/7
Right/Left hemiparesis, n	NA	7/12	14/16	21/30
Motor impairment, FMA-UE (0-66), mean±SD	NA	53.4±8.7	53.6±9.1	55.9±8.8
Sensory impairment, FMA-UE≤11, n	NA	10	12	4
Pain during passive ROM, FMA-UE ≤23, n	NA	6	9	4
Spasticity, Modified Ashworth Scale ≥1,n	NA	3	14	5

Abbreviations: FMA-UE, Fugl-Meyer Assessment for Upper Extremity; ROM, range of motion; MAS, Modified Ashworth Scale

Procedures and data acquisition

Our goal was to establish a standardized test protocol for the drinking task, without physical restraints on the normal movement. The intention was to keep the drinking task natural and close to the real-life situation. Accordingly, the drinking glass was located on the table so that a plate could fit between the person and the glass and the sitting position and task performance was unconstrained as it would be in a real-life. We also aimed to develop a user-friendly protocol for the tester and for the participating individual. Also the data analysis method was designed to be manageable for trained health professional (physiotherapist) and not requiring a background knowledge in engineering or likewise.

A standardized test protocol for kinematic testing was developed during the first study as described in Paper I.[82] This protocol was slightly adjusted for the study II-IV, as the location for testing was moved from the Högsbo Hospital to the Sahlgrenska University Hospital. The quality of the kinematic capture system was as well improved in later studies since five cameras instead of three were used in Study II-IV. This improvement eliminated the problems experienced during the first study with segmentation and gaps and resulted in more or less 100% quality of the capture data.

All kinematic measurements in study I and II were performed by the author of this thesis. In study III and IV the kinematic capture data was gathered by the author of this thesis and another trained physiotherapist in the SALGOT study group (HCP).

Drinking task

The drinking task included: reaching, grasping, lifting the glass from the table; taking a drink (one sip); placing the glass back on the table behind a marked line and finally returning to the initial position (Figure 5). The drinking glass (diameter 7cm; height 9.5cm) was filled with 100ml water, and placed on the table 30 cm from the table edge in the midline of the body. The distance between the body and the glass was approximately 80% of the arm's length, which allowed reaching the glass without extra trunk movement. Subjects were sitting in a height adjustable chair with their back against the chair back, but the position was not restrained and compensatory movements were allowed if needed. In the initial position, the upper arm was in neutral adducted position with approximately 90 degrees flexion at the elbow; the tested hand was resting on the table with the palm downward. The drinking task was performed at a comfortable self-paced speed and both arms were tested starting with the non-affected arm. Five trials of the drinking task were recorded but in statistical calculations a mean of three middle trials was used. One testing session of the drinking task took approximately 10 minutes.

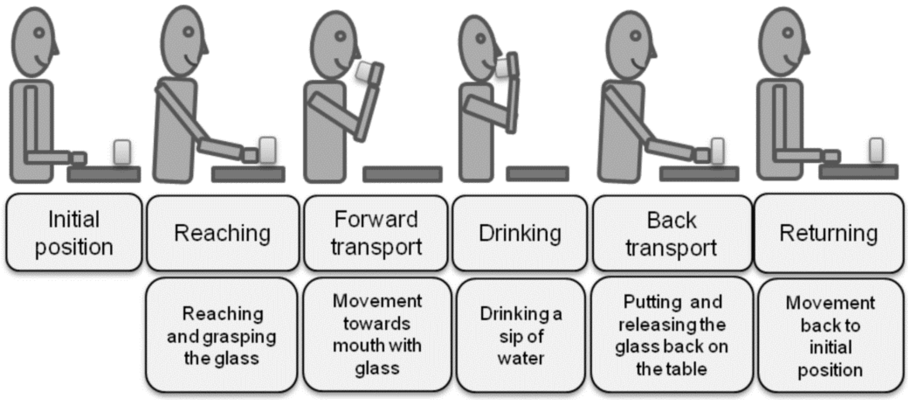

Figure 5. Initial position and phases of the drinking task.

Markers

Nine spherical 12 mm retro-reflective markers were placed on the defined skeletal landmarks as defined by the Sint et. al[83] on the tested hand (third metacarpophalangeal joint), wrist (styloid process of ulna), elbow (lateral epicondyle), right and left shoulder (middle part of acromion), thorax (upper part of sternum), face (notch between eyebrows) and two markers were placed on the glass (upper and lower edge) (Figure 6A). A slightly different set-up for markers was used in Study I; no marker on the contralateral shoulder, extra marker on the index finger (distal interphalangeal joint – DIP II) and the face marker location was on the left cheek instead.

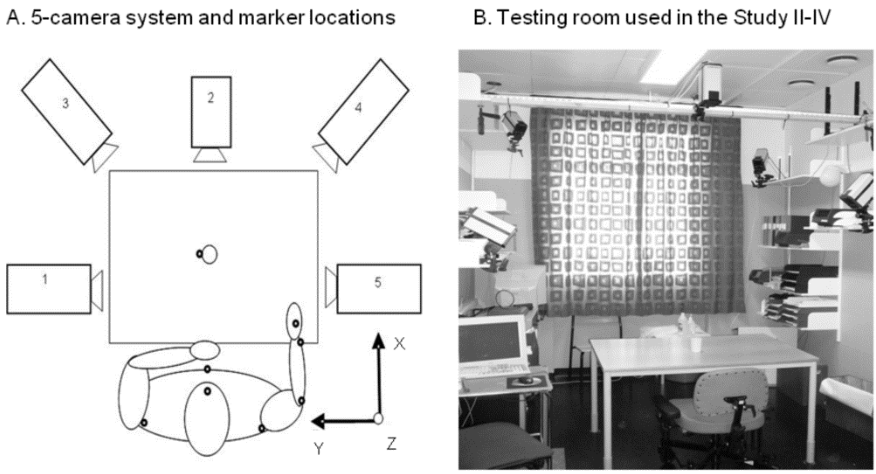

Figure 6. The 5-camera system set-up for drinking task as used in Study II-IV. View from above shows the participant sitting with the arm in the initial position; marker sites are shown as black dots for the capture of right arm movement (A). A photo of the testing room used in Study II-IV with drinking glass on the table (B).

Capture system and data processing

Three-dimensional motion analysis was performed with a five camera optoelectronic ProReflex Motion Capture System (MCU240 Hz, Qualisys AB, Gothenburg, Sweden) as displayed in Figure 6. Data was transferred to Windows-based data acquisition software (Qualisys Track Manager). The coordinate system was defined with X-axis directed forward, Y-axis directed laterally and Z-axis directed upward (Figure 6A). A web camera was also used during measurements to complement motion data with synchronized video data.

The capture data was transferred to Matlab software (The Mathworks Inc.) for custom-made analysis and filtered with 6 Hz second order Butterworth filter in both forward and reverse directions, resulting in a zero-phase distortion and fourth order filtering. The drinking task was broken down into five logical phases: reaching for the glass, forward transport of the glass to the mouth, drinking, back transport of the glass to the table and returning the hand to the initial position. The phase analysis was developed during the first study and slightly adjusted for the Study II-IV. The phase definitions as used in Study II-IV are displayed in Table 4.

Table 4. Phase definitions for drinking task in Study II-IV.

Phase name	Start	Detected by	End	Detected by
Reaching (includes grasping)	Hand movement begins	Hand marker velocity surpasses 2% of the peak velocity	Hand begins to move towards the mouth with the glass	Velocity of the glass exceeds 15 mm/second
Forward transport (glass to mouth)	Hand begins to move towards the mouth with the glass	Velocity of the glass exceeds 15 mm/second	Drinking begins	Distance between the face and glass marker exceeds 15% of steady state during drinking
Drinking	Drinking begins	Distance between the face and glass marker exceeds 15% of steady state during drinking	Drinking ends	Distance between the face and glass marker exceeds 15% of steady state during drinking
Back transport (glass to table, includes release of grasp)	Hand begins to move to put the glass back to table	Distance between the face and glass marker exceeds 15% of steady state during drinking	Hand releases the glass and begins to move back to initial position	Velocity of the glass below 10 mm/second
Returning (hand back to initial position)	Hand releases the glass and begins to move back to initial position	Velocity of the glass below 10 mm/second	Hand is resting in initial position	Hand marker velocity returned to 2% of the peak velocity

Kinematic measures

Kinematic variables used in studies I-IV are displayed in Table 5. The movement times, peak tangential velocities and number of movement units (NMU) were obtained from the hand marker data (Figure 7). Total movement time was calculated for the entire drinking task based on the phase analysis (Table 4). Time to peak velocity reflects the proportion of time spent in acceleration and deceleration and the time to 1st peak illustrates the initial movement effort in reaching phase (Figure 7).

Table 5. Kinematic variables used in Study I-IV.

Kinematic measures	Paper I	Paper II	Paper III	Paper IV
Movement time, based on phase analysis				
Total movement time	√	√	√	√
Reaching	√	√		
Forward transport	√	√		
Drinking	√	√		
Back transport	√	√		
Returning	√	√		
Velocity and strategy				
Peak velocity, reaching	√	√		
Peak velocity, forward transport	√			
Peak velocity, back transport	√			
Peak velocity, returning	√			
Time to PV in reaching	√	√		
Time to PV in reaching (%)	√	√		
Time to 1st peak in reaching		√		
Time to 1st peak in reaching (%)		√		
Peak angular velocity of elbow joint in reaching (PAVE)		√	√	
Smoothness				
Number Movement Units (NMU)		√	√	√
Interjoint coordination (IJC)				
IJC for shoulder and elbow joint	√	√		
Compensatory trunk displacement and joint angles				
Trunk displacement (TD)	√	√	√	√
Shoulder flexion in reaching, drinking	√	√		
Shoulder abduction in reaching, drinking	√	√		
Shoulder adduction in reaching, drinking	√	√		
Elbow extension in reaching	√	√		
Elbow flexion in drinking	√	√		

Abbreviations: PV, peak velocity

Movement smoothness was quantified by computing the number of movement units on the velocity profile during reaching, forward transport, back transport and returning phase. One movement unit comprises acceleration, a predominant velocity peak and deceleration. It was defined as a difference between a local minimum and next maximum velocity value that exceeded the amplitude limit of 20 mm/s on the hand marker velocity profile; the time between two subsequent peaks had to be at least 150ms. The minimum number of MU during the drinking task is four, at least one unit per movement phase.

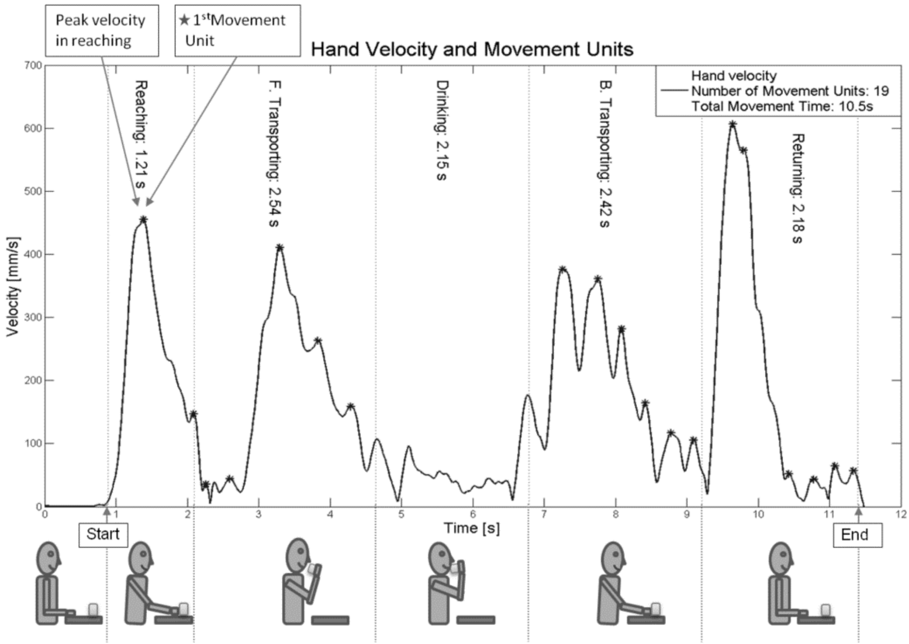

Figure 7. An example of the tangential velocity profile in an individual with stroke. The movement phases and the kinematic measures of movement time, peak velocity and movement units are indicated.

Inter-joint coordination (IJC) between the shoulder and elbow joint angles was characterized both qualitatively and quantitatively. Angle/angle diagrams were plotted for shoulder flexion and elbow extension in reaching phase. Temporal IJC for shoulder flexion and elbow extension was computed by use of cross-correlation analysis of zero time lag.[75,84] The correlation coefficient closer to 1.0 indicates stronger correlation and indicates that joint motion of the two joints is tightly coupled.

Compensatory trunk movement was computed for the entire drinking task as the maximal displacement of the thorax marker from the initial position. The elbow joint angle excursions were determined by the angle between the vectors joining elbow and wrist markers and the elbow and shoulder markers, and the shoulder joint angle excursions by the angle between the vectors joining the shoulder and elbow markers and the vertical vector from the shoulder marker toward the hip. Peak angular velocity of the elbow joint (PAVE) was computed from angular data in the reaching phase.

In previous studies, test-retest reliability has been reported to be excellent for the movement time and trunk displacement in a reach-to-grasp task with comfortable speed in people after stroke (ICC 0.94; 0.91)[59] as well as for the movement smoothness (ICC 0.88) in a reach-to-grasp task in children with cerebral palsy.[78] Strong correlations have been reported in previous studies between Fugl-Meyer Assessment and trunk displacement during reaching.[56,57,68,74] Responsiveness has previously been studied only in few studies, using the internal responsiveness statistics, such as effect size or SRM. Large effect sizes have been reported for the movement duration and smoothness in reaching as well as in hand-to-mouth tasks in subjects with stroke.[61,76]

Clinical assessments

An overview of descriptive data and outcome variables used in Study I-IV is listed in Table 6. A summary of the measurement properties of the kinematic measures and clinical assessments used in all studies are displayed in Table 7.

The sensorimotor function was assessed using the Fugl-Meyer Assessment for Upper Extremity (FMA-UE).[36] The FMA-UE items are divided into 4 subscales (arm, wrist, hand and coordination) and are scored on a 3-point ordinal scale (0 - cannot perform; 1 - performs partially; 2 - performs fully). The scoring is based on the ability to perform isolated movements both within and outside of the synergy patterns. The maximum total score of 66 corresponds to unimpaired motor function. The Fugl-Meyer Assessment is one of the most widely used observational rating scales available for stroke and the psychometric properties of FMA have been studied extensively and demonstrate excellent reliability and validity.[36,85,86]

The non-motor domains of FMA-UE, sensation (0-12), passive range of motion (0-24) and pain during passive joint motions (0-24), was assessed for descriptive background data. The higher score indicated normal sensation, normal range of motion and no pain.[36]

The increased muscle tone in elbow and wrist joints (both mechanical and neural) was assessed for descriptive background data using the Modified Ashworth Scale (MAS) and a score equal or larger than 1 was indicating the presence of spasticity.[87] The MAS is the best alternative for spasticity assessment in clinical setting available and has been shown to have a good to fair reliability for these joints.[87-89]

Table 6. Overview of the assessments used in paper I-IV, sorted according to ICF.

Name	Description	Paper I	Paper II	Paper III	Paper IV
Body functions and structures					
Kinematic measures (number of variables)	movement performance and quality	25	19	4	3
Anthropometrics	height, arm length	√	√	√	√
Lesion type, side	stroke		√	√	√
Fugl-Meyer Assessment for Upper Extremity (FMA-UE)	sensorimotor function		√	√	√
Non-motor domains of FMA-UE	sensation, passive ROM, pain during passive ROM		√	√	√
Modified Ashworth Scale	spasticity		√	√	√
Activities					
Action Research Arm Test (ARAT)	activity capacity, dexterity			√	√
ABILHAND	self-perceived manual ability			√	
Personal factors					
Age/gender	male/female	√	√	√	√
Living situation	home/hospital		√	√	√

The activity capacity was evaluated using the Action Research Arm Test (ARAT), which is a performance test for upper extremity function and dexterity.[37] The ARAT uses 4-point ordinal scoring on 19 items divided into four hierarchical subtests: grasp, grip, pinch and gross movement. The scoring is based both on the movement performance and on the time limit and the maximum total score of 57 indicates normal performance.[37,90] ARAT has been shown to have good validity, sensitivity to spontaneous and therapy-related gains both in acute and chronic phase after stroke.[37,91] The ARAT has shown good responsiveness[81] and excellent inter- and intra-rater reliability.[37,92]

The self-perceived manual ability was assessed using the 23 item Rasch validated ABILHAND questionnaire for people after stroke.[93,94] ABILHAND measures the person's perceived difficulty in performing everyday manual activities on a 3-level scale (impossible, difficult, and easy) without external help and irrespective of the limb and strategy used. The score is expressed in logits[95] and is considered as an interval linear measure in statistical calculations.[93,94]

Table 7. Measurement properties of the assessments used in paper I-IV.

Outcome	**Kinematic measures**	**FMA-UE**	**ARAT**	**ABILHAND**
Reliability	High*	High	High	High
Construct validity	High/Moderate*	High	Moderate	Moderate
Responsiveness	Large*	Moderate	Moderate	Large
MCID	-	7	6	0.26-0.35
Score range	Varies	0-66	0-57	Logits (-6 to +6)
Administration time	10-15 min (drinking task)	10-15 min	8-10min	10-15 min
Equipment	technology equipment	cup, ball, pen, paper, reflex hammer	standardized equipment	standardized questionnaire
Type	quantitative	observational rating scale	observational rating scale	self-perceived, questionnaire
References	59,61,76,78	11,96-98	11,77,81,92,99,100	93,94,101

High/large[11] = ICC or kappa value >0.75; Cronbach's α > 0.8; Correlation coefficient >0.60; Area under the curve (AUC) >0.9; Effect size > 0.8
Moderate[11] = ICC or kappa value 0.4-0.74; Cronbach's α > 0.70-0.79; Correlation coefficient 0.30-0.60; Area under the curve (AUC) 0.7-0.9; Effect size 0.5-0.8
Low/small[11] = ICC or kappa value < 0.40; Cronbach's α < 0.70; Correlation coefficient <0.3; Area under the curve (AUC) >0.7; Effect size < 0.5
*varies depending on variable (detailed information is presented in the text)

Statistical analysis

Statistical analyses in all studies were performed using SPSS (Statistical Packages for Social Sciences). A significance level of 0.05 was used in statistical analysis. An overview of the statistical methods used in Paper I-IV is presented in Table 8.

Table 8. Overview of statistical methods used in Paper I-IV.

Statistics	Paper I	Paper II	Paper III	Paper IV
Descriptive	√	√	√	√
Test-retest consistency				
Paired t-test	√			
95% Limits of Agreement (LOA)	√			
Bland Altman plot	√			
Explorative				
Principal Component Analysis (PCA)		√		
Differences between groups				
Paired t-test		√		
Wilcoxon's signed ranks test		√		
Independent samples t-test		√		√
Mann-Whitney U-test		√		
Effect size (partial Eta squared, η^2)		√		
Sensitivity/Specificity		√		
Analysis of relationships				
Spearman rank-order correlation			√	
Univariate and multiple linear regression			√	
Analysis of change, responsiveness				
Paired t-test				√
Effect size (partial Eta squared, η^2)				√
Receiver Operating Characteristic (ROC) curve				√
Sensitivity/Specificity				√
95% Limits of Agreement (LOA)				√
Univariate and multiple linear regression				√

Descriptive statistics

Descriptive statistics were used for demographic data, clinical characteristics and for kinematic movement performance measures to describe the study samples.

Test–retest consistency (Study I)

The difference between test and retest was analyzed with a paired *t*-test. The agreement between test and retest was evaluated with 95% limits of agreement (LOA) method.[102,103] The 95% LOA were calculated as the mean of difference ±1.96 standard deviations of difference. To check the assumptions of the limits of agreement the differences were plotted against the average of the two measurements for every variable.

Explorative (Study II)

Kinematic data was explored quantitatively with factor analysis. Principal Components Analysis (PCA) with varimax rotation based on correlation matrix was employed to make informed decisions on reducing the number of kinematic variables, while retaining as many variables as needed to describe performance. PCA gives the number of variables (components) that are needed in order to capture most of the variance in the original kinematic dataset. The determination of the specific variables that are to be extracted is both a statistical and qualitative decision of the researcher. Correlation matrix was examined to see which kinematic variables clustered together in a meaningful way and may measure aspects of the same underlying dimension (factor). Extraction of components was made according to Kaiser's criterion, thus the variables with loading values greater than 0.6 were extracted from rotated component matrix.[104]

Differences between groups (Study II, IV)

Non-parametric tests were used when data was not normally distributed. Within-group differences were calculated for the dominant and non-dominant arm kinematics in healthy individuals (Study II) and for the affected arm kinematics over time in people with stroke (Study IV). Between-group differences were performed for healthy subjects and individuals with mild and moderate impairment level after stroke (Study II) and for change values over time in stroke subgroups (Study IV). Partial Eta squared (η^2) statistics was used to calculate effect sizes of differences between groups. The Cohen's guidelines for interpreting the effect sizes are: 0.01=small, 0.06=moderate, 0.14=large effect .[105]

Analysis of relationships (Study III)

Correlation between kinematics and clinical scales were evaluated using the Spearman rank order correlation coefficient. Univariate and multivariate linear regressions with backward deletion were used to assess how much variance in clinical assessments can be explained by kinematic variables and to determine which kinematic variable(s) explained the greatest amount of variance (Study III). Preliminary analyses were conducted to ensure no violation of the assumptions. The limit for multicollinearity between independent variables was set at ≥0.7 and in case of collinearity the variable with higher correlation with dependent variable was used. Probability for entry in backward regression was set at 0.05 and removal at 0.10. Adjusted R^2 value, unstandardized coefficient (B) and unique partial correlation coefficients were used in order to provide a better estimate of the true population value and to offer an estimation of the magnitude of the contribution of each predictor to the model.

Analysis of change, responsiveness (Study IV)

Receiver operating curve (ROC) analysis and area under the curve (AUC) statistics were used to expresses probability of the kinematic variables to correctly classify subjects between the subgroups. A test value of 1.0 indicates a perfect classification and a value higher than 0.70 can be considered to be acceptable.[33] The ROC curves were examined to determine cut-off values for the change in kinematic variables at which the probability to correctly classify subjects into each group respectively, was highest. The sensitivity and specificity for these cutoffs were calculated. The upper 95% limit of agreement (LOA), defined as the mean change +1.645 standard deviations of the change (one-tailed), was calculated for the stroke subgroup with small or no-improvement (subgroup 1).[106]

Univariate linear regression analysis was used to determine the amount of variance in the change of the kinematic measures that was associated with the change in the ARAT score in subjects that showed a real clinical improvement in arm activity capacity. The unstandardized coefficient B was employed to determine the amount of change in kinematic measure (dependent variable) that was associated with a unit change in ARAT (independent variable). Multiple linear regression analysis was employed to control for the possible effect of age, gender, person's height and baseline level of the kinematic measures. Preliminary analyses were conducted for the regression analyses to ensure no violation of the assumptions of normality, linearity, multicollinearity and homoscedasticity.

Ethical considerations

All studies were approved by the Regional Ethics Review Board in Gothenburg and written informed consent was obtained from all subjects prior study entrance. The approval protocol number for study I and II was 318-04 and for study III and IV, 225-08. All participants received both oral and written information about the purpose, procedure, risks and benefits of the study. No specific risks due to the testing were identified. Participants were asked about the possible allergy for tape, as the markers in kinematic testing were attached on the skin with double-sided tape. Participants had also possibility to take up and discuss issues that had risen during the testing session with the test leader. Participants were informed of the routines around data handling and confidentiality and could without explanation withdraw from the study. All participants could have access to their own results directly after the testing session or at the end of the study. The SALGOT study has been registered on the ClinicalTrials.gov (NCT01115348) and the protocol has been published.[107]

RESULTS

Development of the kinematic test protocol and analysis method

A standardized test protocol for the drinking task was developed by testing a range of different marker, camera and subject positions during the first study. This protocol was refined further for the five camera system used in the second study. The final protocol (Study II-IV) met the specific measurement goals for the drinking task and ensured full quality of the capture data throughout the data collection.

In order to investigate movement variables during different phases of drinking, the task was broken down into five logical sequential phases as described in the method section. The final definitions for the phase identification used in the Study II-IV are displayed in Table 4 in the Methods section. A custom made software program was required for the analysis of capture data. This was accomplished by close collaboration between clinicians and engineers during the first two studies.

The test protocol demonstrated a good consistency in test-retest in healthy individuals and provided clear and accurate results. The differences between test-retest did not vary in any systematic way over the range of measurement and all measurements were within the 95% limits of agreement. All mean differences were close to the zero and the widths of the 95% CI of difference and the 95% LOA were narrow. Detailed results from test-retest are provided in Paper I (Table 3 in Paper I).

Kinematic characteristics of the drinking task

Healthy group

In healthy people the movements were smooth and the tangential velocity profiles continuous and bell-shaped with one predominant peak per movement phase. It took approximately 6.5 seconds (SD 0.83, min-max 5.5-8.3) for healthy individuals to accomplish the drinking task. The peak velocity was reached approximately at 46% of the total reaching time, which means that deceleration lasted approximately 54% of the reaching phase (Paper II, Table 2).

The smoothness was determined by the number of movement units (NMU) in the hand marker velocity profile for all movement phases apart the drinking phase. The minimum number of movement units per phase is one. In healthy, the mean NMU for right and left arm for the two first phases was 2.2(SD=0.2) and 2.3 (SD=0.3), respectively. For all four movement phases the mean values were 6.0(SD=1.0) and 6.5 (SD=1.1), respectively. These values indicate that small submovements could be present in some individuals when the glass was placed back on the table and hand moved back to the initial position. A typical example of a healthy individual's velocity profile is shown in Figure 8.

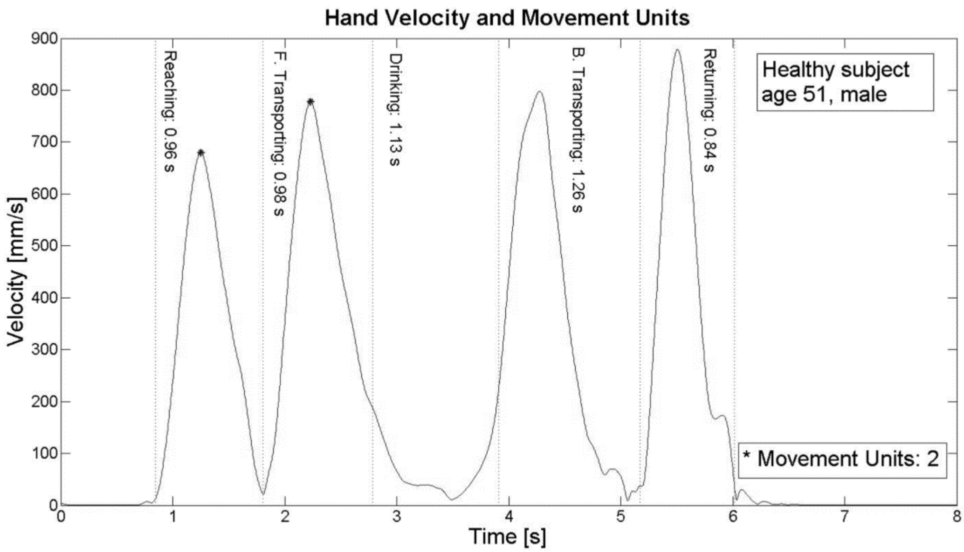

Figure 8. Tangential velocity profile of the drinking task in a healthy person.

In our set-up, the glass was placed approximately at 80% of the arm lengths distance, which means that reaching could be performed without compensatory trunk movement. Accordingly, the mean value for the trunk displacement (TD) in healthy individuals was 2.7 cm (SD 1.7). This small amount of trunk movement can be considered as part of normal reaching and reflects the small adjustments made in the upper body while performing tasks in unconstrained conditions.

The drinking glass was reached at approximately 54° of flexion in the elbow and 46° of flexion in the shoulder; during drinking the shoulder was abducted approximately 30° and flexed 52° (Paper II, Table 2). The interjoint coordination (IJC) between shoulder and elbow joint was high (mean r=0.96), which means that the angular motion in shoulder flexion and elbow extension during reaching was highly synchronized. The angle-angle graph illustrating IJC in a healthy person is presented in Paper I (Paper I, Figure 3).

Stroke group

The movement times in every movement phase and for the entire task were slower in people with stroke. Still, the percentage of time spent in every movement phase was similar to the healthy people (Table 9).

Table 9. The percentage of time spent in every movement phase in healthy participants and in individuals with stroke (Data based on the results from Paper II).

Percentage of time (%) in movement phases	Healthy n=19	Stroke n=19
Reaching	16.1±2.0	16.7±2.3
Forward transport	18.2±2.5	19.7±2.6
Drinking	22.9±4.2	22.1±4.6
Backward transport	24.4±3.0	24.9±3.3
Returning	18.4±2.7	16.7±2,2

In addition, both tangential as well as angular velocities were lower in people with stroke compared to the healthy individuals. The peak velocity occurred approximately at 38% of the total reaching time, which means that the deceleration phase took approximately 62% of the total reaching time (Paper II, Table 2). The velocity profiles in people with stroke were segmented and multiple peaks could be observed, which was reflected in the high number of the movement units (NMU). The mean value for the NMU in the first two movement phases (reaching and forward transport) was 7.9 (SD=8.9) and for the last two phases (back transport and returning) 8.3 (SD=4.5), resulting in total NMU of 16.2 (SD 12.8) (Paper III). Similarly to the healthy individuals, a slightly higher number of movement units could be observed in the last two movement phases compared to the two first phases.

Individuals with stroke reached the glass with a more flexed elbow and the shoulder was more abducted in the drinking phase compared to the healthy participants. The glass was reached approximately at 64° of elbow flexion; and during drinking the shoulder was abducted approximately 48° and flexed 54°. Even though the glass was positioned within the arm reach, individuals with stroke did lean forward approximately 8 cm while performing the drinking task. Exact values of kinematic variables are displayed in Paper II, Table 2.

Interjoint coordination between shoulder and elbow joint was low (mean r=0.69) in individuals with moderate stroke impairment (FMA-UE score between 39 and 57) and they demonstrated problems in moving shoulder and elbow joints simultaneously in a continuous movement while reaching for the glass. This phenomenon could also be observed in the angle-angle graphs, which are displayed in Paper II (Paper II, Figure 3).

Exploring and validating kinematic variables

Construct validity (dimensionality)

Principal component analysis (PCA) revealed that the drinking task in people with stroke can for the most part be captured by two major factors (Figure 9). The movement time and smoothness appeared to measure aspects of the same underlying dimension and together with measures of movement velocities composed one of the major factors. The second major factor in the original data consisted of compensatory movement patterns (joint angles and trunk displacement) and interjoint coordination variables. In total, 86% of the variance in kinematic data was explained by five components with eigenvalues exceeding 1.

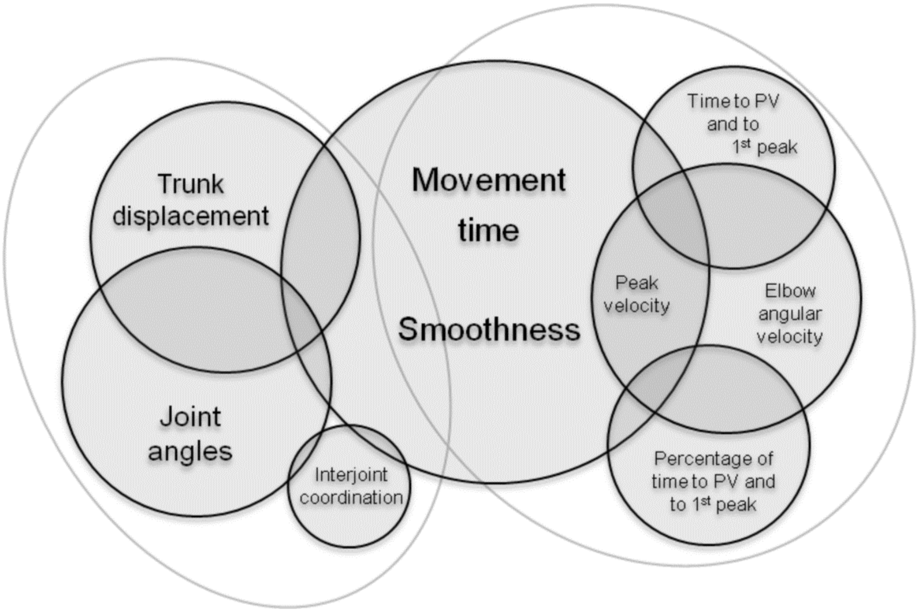

Figure 9. Illustration of the results from the Principal Component Analysis (PCA). The two main factors (dimensions) found in the dataset are encircled Abbreviation: PV, Peak velocity.

Discriminative validity

The majority of kinematic variables extracted from the PCA were demonstrated to be effective in discriminating between groups with different level of arm function: moderate stroke impairment (FMA-UE score 39-57), mild stroke impairment (FMA-UE score 58-64) and healthy (Paper II, Table 2). Large effect sizes for the differences between groups revealed that the smoothness, total movement time, peak angular velocity of the elbow (PAVE) and trunk displacement had the strongest ability to discriminate between the different stroke impairment levels as well as between healthy individuals and individuals with stroke (Figure 10). Higher elevation angle in the shoulder joint (flexion and abduction) during drinking and interjoint coordination in reaching were more discriminative for the moderate stroke impairment than for the mild impairment group. On the other hand, the peak velocity and elbow angular velocity in reaching demonstrated higher discrimination for the mild impairment than for the moderate impairment. Exact values for kinematic measures and differences between groups are presented in Paper II, Table 2.

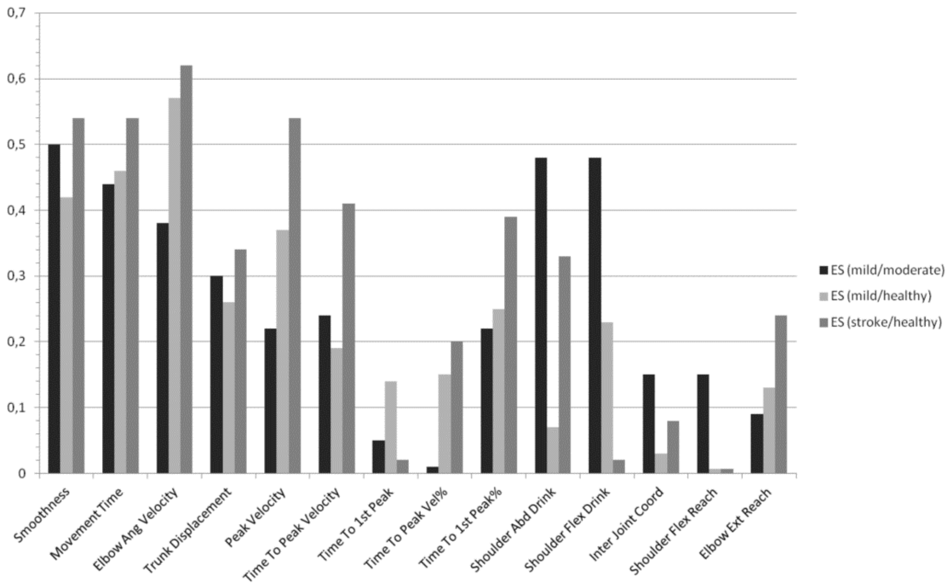

Figure 10. Effect sizes (partial η²) of differences between groups: mild and moderate stroke impairment (first bar, black), mild stroke impairment and healthy participants (middle bar, light grey), total stroke group and healthy participants (last bar, dark grey). Effect sizes 0.19 and higher designate statistically significant differences between groups.

Concurrent validity

Multiple regression analysis revealed that kinematic variables could explain the largest amount of variance in the activity capacity, assessed with ARAT. The kinematic variables, NMU and TD together explained 67% of the total variance in ARAT, demonstrating a unique contribution of 37% and 11% respectively (Paper III). High collinearity existed between the NMU and movement time (MT) and therefore only one of the variables (NMU) was used in the multivariate models. This means that the MT can be considered to have approximately the same impact in the regression models as NMU.

The correlations between FMA-UE and the kinematics were moderate and in the multiple regression analysis, the TD alone demonstrated significant contribution to the regression model, explaining 20% of the total variance in FAM-UE.

The kinematic measure of smoothness explained 8% of the variance in the self-perceived manual ability questionnaire, ABILHAND, but this small contribution to the model was not significant. A schematic figure illustrating findings from the multiple regression analysis is presented in Paper III, Figure 2.

Responsiveness and expected change in kinematics – longitudinal validity

A significant change in movement time, smoothness and trunk displacement (MT, NMU and TD) was seen in both subgroups apart from trunk displacement in the small or no-improvement group. The mean change and the effect sizes (ES, partial η^2) for the change in these three measures along with three other measures that also showed significant improvements in both groups (peak velocity, peak angular elbow velocity and time to peak velocity) are displayed in Table 10. It must be noted, however, that the relatively high effect sizes in the subgroup 1 (small or no-improvement) as seen in the Figure 11, depend mainly on the low variability within this group. Therefore, these ES values cannot be compared with the ES values in subgroup 2 (real clinical improvement). Improvements seen in subgroup 1 (small or no-improvement group) indicate, however, that significant improvements can be detected even in people with mild impairments using these kinematic measures. The improvement in the measure of T2PV (Table 10) demonstrates the lowest ES and seems to have low clinical value as the absolute change is very small.

Results from the ROC curve analysis are displayed in Figure 11. Movement smoothness and movement time demonstrated the highest sensitivity to identify subjects with real clinical improvement. The trunk displacement was as well effective in discriminating between the subgroups but the sensitivity was lower. The right graph in Figure 11 shows two other kinematic measures that demonstrated significant improvements during the first three months after stroke. Both peak velocity and elbow angular velocity demonstrated lower AUC values along with lower sensitivity and specificity compared to the smoothness, movement time and trunk displacement measures.

Table 10. Mean values (±SD) in kinematic measures at baseline (mean, 10 days post-stroke), at 3 months follow-up and the change between these two time points in subgroup 1 (small or no-improvement) and in subgroup 2 (real clinical improvement). The three first measures have been reported earlier in Paper IV.

Kinematic variables	Baseline	Follow-up at 3 month	Mean change	95% CI	p-value	Effect size
Subgroup 1 (n=27)						
MT (s)	7.98±1.9	6.44±1.2	1.5±1.4	1.0;2.1	0.0005	0.55
NMU (units)	9.03±3.1	7.02±2.3	2.0±2.2	1.1;2.9	0.0005	0.46
TD (cm)	4.71±2.5	3.95±1.3	0.8±2.0	-0.03;1.5	0.59	0.12
PV (mm/s)	523±114	608±98	84±84	50;117	0.0001	0.51
PAVE (°/s)	85±25	99±27	14.3±24	4.7;24	0.005	0.27
T2PV(s)	0.5±0.1	0.4±0.1	0.06±0.1	0.02;0.1	0.01	0.22
Subgroup 2 (n=24)						
MT (s)	14.3±9.5	7.2±1.7	7.1±9.2	3.2;11.0	0.001	0.39
NMU (units)	19.0±14.4	7.9±2.9	11.1±13.3	5.5;16.7	0.0004	0.42
TD (cm)	8.6±5.6	4.5±2.4	4.1±4.6	2.1;6.1	0.0002	0.45
PV (mm/s)	448±130	576±130	128±93	89;167	0.0001	0.66
PAVE (°/s)	61±25	83±24	22±22	13;32	0.0001	0.52
T2PV(s)	0.6±0.2	0.5±0.2	0.1±0.2	0.03;0.2	0.01	0.24

Abbreviations: MT, movement time; NMU, number of movement units; TD, trunk displacement; PV, peak velocity; PAVE, peak angular elbow velocity; T2PV, time to peak velocity; effect size, partial η^2

Univariate linear regression analysis revealed that the real clinical improvement in subgroup 2 was significantly associated with the improvement in kinematic measures. Accordingly, the clinical change measured with ARAT could explain 36%, 31% and 35% of the variance in the change of MT, NMU and TD, respectively. The unstandardized coefficient B, as reported in Paper IV (Paper IV, Table 4), indicates, on average, the expected change in kinematic variable associated with one unit change in the reference measure (ARAT). This coefficient can successfully be used to calculate a change in kinematics for any corresponding preferred change on ARAT. In our study, we provided a change in kinematics corresponding to a 6 points change on ARAT indicating a real clinical improvement.

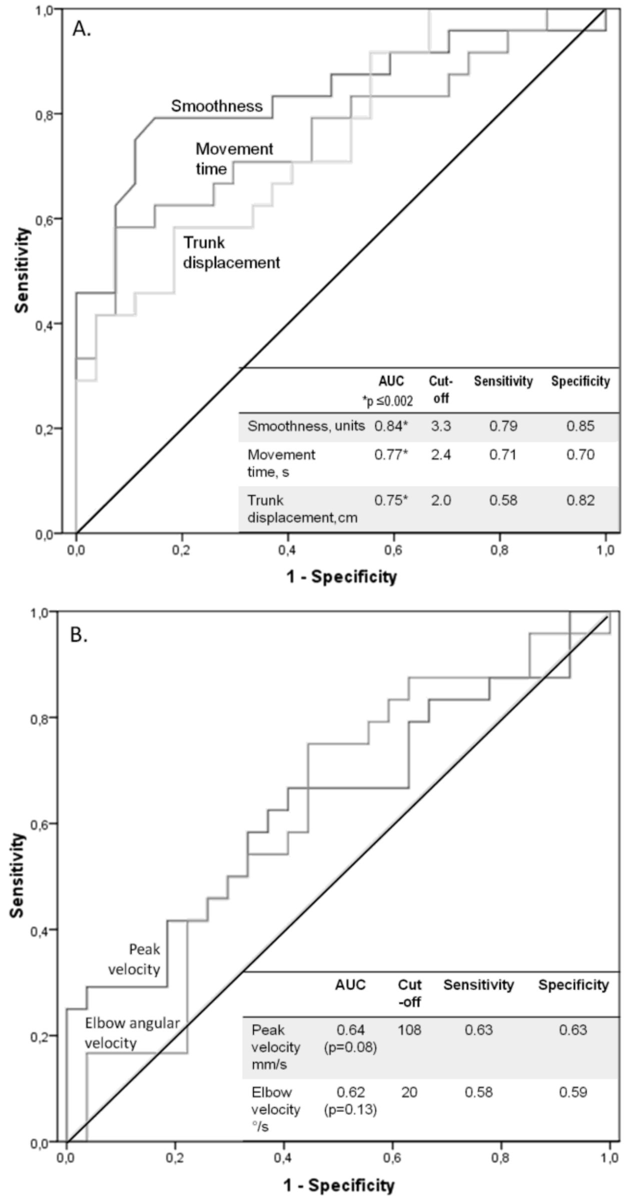

Figure 11. Results from the ROC curve analysis for the kinematic measures reported in the Paper IV (A) and for the peak velocity, PV and elbow angular velocity, PAVE (B). The Area under the curve (AUC), most optimal cut-offs along with sensitivity and specificity for these cut-offs are displayed in the build-in table.

Multiple linear regression analysis confirmed that age, gender, height and baseline level of the kinematic measures did not influence the effect of ARAT on kinematic measures. ARAT was the only significant independent variable in the model when the controlling variables were included and the unstandaridized regression coefficients (B) of the ARAT were comparable with coefficients (B) in the simple regressions.

For this thesis, complementary univariate linear regression analyses were applied on two additional kinematic measures that demonstrated significant improvements over time: peak velocity and elbow angular velocity. Only one of them, the elbow angular velocity, demonstrated significant association (R^2=0.29, p=0.007, B= 1.8) with change in ARAT. This association was smaller compared to the kinematics reported in the Paper IV, but still there are some indications that even elbow angular velocity could be responsive to capture improvements in upper extremity activity during the first three months after stroke.

As noted above, the regression coefficient B, can be used to determine the absolute change in kinematics that corresponds to a certain clinical change. For clinical interpretation, preferably, estimates from different analyses could be combined when improvements in kinematics are evaluated. The results from different statistical analyses for these estimates and the approximate range for the cut-offs indicating a real clinical improvement in kinematics (last column) are displayed in Table 11.

Table 11. Results from different analysis of the expected change in kinematics associated with a real clinical improvement. The three first measures in Table 11 have been reported earlier in Paper IV.

Kinematic variables	Upper 95% LOA in group 1	ROC cut-off	Real clinical improvement	Estimated range
Movement time (s)	3.8	2.4	5	2 - 5
Movement units (units)	5.6	3.3	7	3 - 7
Trunk displacement (cm)	4.1	2.0	3	2 - 4
Elbow angular Velocity (°/s)	54	20	11	11 - 54
Peak velocity (mm/s)	222	108	19	19 - 222

Abbreviations: 95% LOA, Limits of agreement for the subgroup 1 (small or no-improvement); ROC, Receiver Operating Curve; real clinical improvement, magnitude of improvement in kinematics associated with 6 points change in Action Research Arm Test; Estimated range indicating a real clinical improvement in kinematics (last column).

Summary of the results

An overview of the results from the validity and responsiveness analysis in kinematic measures is displayed in Table 12. In addition, a schematic overview of the main objectives, analysis and results in all four studies (Paper I-IV) included in this thesis is presented in Figure 12.

Table 12. Overview of the results from Paper II-IV on validity and responsiveness for kinematic variables studied. The empty boxes indicate that the values were lower than the set-up limits and the validity and responsiveness could not be proved for these measures.

Kinematic variables	Validity			Responsiveness		
	Discriminative		Concurrent	Change	ROC	Regression
	p<0.05	ES>0.3	Spearman's rho p<0.05	p<0.05	AUC>0.7	p<0.05
Movement time	both	both	√	√	√	√
Smoothness (NMU)	both	both	√	√	√	√
Trunk displacement	both	mod	√	√	√	√
Peak angular elbow velocity (PAVE)	both	both		√		√
Peak velocity (PV)	both	mild		√		
Time to PV (T2PV)	both		√	√		
Time to PV %						
Time to 1st Peak			√			
Time to 1st Peak %	both					
Shoulder abduction in drinking	both	mod				
Shoulder flexion in drinking	mod	mod				
Inter joint coordination (IJC)						
Shoulder flexion in reaching						
Elbow extension in reaching						

Abbreviations: ROC, Receiver Operating Curve; AUC, area under the curve; mild, discriminates between mild/healthy; mod, discriminates between moderate/mild; both, discriminates in mild/healthy and moderate/mild; concurrent indicates correlation to the Action research Arm Test; change indicates improvement during the first 3 months post-stroke

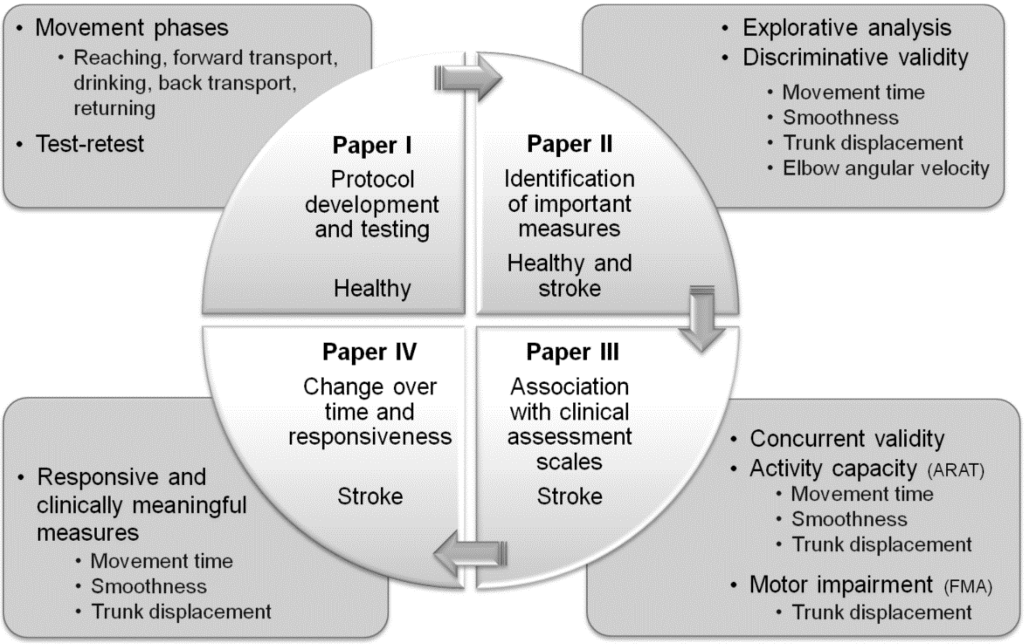

Figure 12. A schematic overview of the main objectives, analysis and results in all four studies (Paper I-IV) included in this thesis.

DISCUSSION

Main findings

The current thesis provides a detailed description on kinematic movement analysis of a daily task, “drinking from a glass”. The phase analysis which divided the drinking task into five sequential phases was unique and essential for the analysis and interpretation of data.

The explorative analysis of kinematic data revealed that the drinking task can for the most part be described with two major factors in people with stroke. The findings reported in this thesis revealed that the number of kinematic measures needed to describe the movement performance in drinking task can successfully be reduced. It also became clear that both temporal and spatial measures are important to be included when upper extremity movement performance is evaluated.

Three kinematic measures in particular emerged throughout studies. These measures were: movement smoothness, movement time and trunk displacement. All three measures demonstrated to be effective in discriminating individuals with different functioning level; all three were strongly related to the upper extremity activity capacity level; and all three were effective in detecting a real clinical improvement in upper extremity after stroke.

Conclusively, the test protocol of the drinking task, as described in this thesis, is feasible for clinical studies and provides objective, valid, responsive and clinically interpretable data of movement performance in people after stroke.

Methodological considerations

The “drinking task”

A large number of studies from the motor control area have shown that the experimental constraints such as selection of objects and the goal of the task have impact on the motor planning and performance[39]. For example, a pointing task has different kinematics than a task that combines grasping, in the same way that a reaching movement is different depending on whether a simulated or real-life object is used.[17,64] For instance, movement time and deceleration phase during reaching are longer when the person is asked to grasp the object compared to the movement when the person is asked to point and hit the target.[108] Similarly, it has been shown that movement is faster and peak velocity is reached earlier during reaching when the person has to pick up an empty cup compared to a filled cup.[109] In the same study, it was also noted that when the cup was full, participants made a postural adjustment concurrently with decreased angular motion in shoulder and elbow joint in order to stabilize the body.[109] It has been reported that that movements are smoother, faster, more forceful, and preplanned for the goal-directed tasks in a natural setting than for the tasks in a simulated context.[63,64] Clearly, the task constraint and goal affects the movement, and therefore both assessment as well as training should include purposeful tasks performed within natural context so the specific difficulties of an individual's daily life can be reflected.[17,39,65]

The analysis of common purposeful tasks from real-life, such as drinking, will enhance the ecological validity of a study and is generally experienced as meaningful by the tested person and health professionals. Earlier life experience and procedural memory of the arm use in the drinking task as well as the clear functional goal of the task facilitate further the relearning and retraining of this daily task after a stroke. Even though the drinking task might seem to be a relatively simple task, the demands on the motor control and sensorimotor function are fairly high. The task requires eye-hand coordination, ability to plan and execute a relatively precise reach toward the glass, and also requires ability to grasp, manipulate and transport the glass in order to drink. The results from this thesis show, however, that in individuals with moderate and mild stroke impairment, clinically valuable data can be obtained by using kinematic movement analysis method of the drinking task.

Kinematic characteristics of the drinking task have been analyzed in several studies in healthy people. The main objective in these studies has been to establish an accurate biomechanical model of the upper extremity, for example to support the development of technology based assistive devices.[110-112] There are also several experimental studies of the drinking task from the area of motor control and motor learning.[109,113] The drinking task has also been evaluated in people with Parkinson disease[114], in children with cerebral palsy[115], and in people after cervical spinal cord injury. The latter study employed a kinematic analysis method similar to the one described in this thesis.[116] To date, there is only one study that has analyzed movement kinematics during drinking in patients with hemiparesis.[62] The main objective in that study was to investigate the coordination between reaching and grasping in the reaching phase.[62]

As shown earlier, many movement characteristics are dependent on the task, which indicates that systematic analyses of the appropriate measures would be required for several different basic tasks. Thus more studies are needed to investigate the performance in different every-day tasks with kinematic movement analysis in people with stroke.

Movement analysis protocol

Kinematics of arm movements can be studied in many different ways: from detailed analysis of all degrees of freedom to simplified models for specific purposes. In this thesis a single-marker-based model was used for the kinematic movement analysis. This approach has shown to be reliable and effective for clinical applications.[49,51,52,60,61,71,74] In clinical settings, the measurement set-up needs to be reliable, easy to use, allow manageable data handling and analysis, be clear in results and meet the clinical questions asked. In these situations, a simpler measurement method and analysis model could be beneficial for more efficient clinical implementation. A more detailed analysis using a cluster-based model may, however, be required for more precise biomechanical modeling, particularly when the axial rotations in the shoulder and joint movements in wrist and hand are of interest. In the future, there is also a need to develop and establish better guidelines for the upper extremity kinematic movement analysis in people with different disabilities. In addition, guidelines with different technical complexity levels would be needed in order to target different goals in biomechanical, motor control and clinical research.

Problems with segmentation and gaps in kinematic capture data have been reported earlier when a small number of cameras have been used for complex arm movements.[64,117] This problem was also experienced during the first study of this thesis, in which a three-camera system was used. A five-camera system used in the later studies (Paper II-IV), including one camera with a view from above, resulted in no data loss during the capture. This improvement ensured that the test protocol developed in this thesis produced consistent and high quality data. In addition, the test procedure along with data handling and analysis was easy to use for a health professional (physiotherapist) in every-day bases. An initial collaboration with engineers was, however, essential for development of a custom-made program for the drinking task. While the routine every-day basis data handling was straightforward and easy to use, the process for the data analysis was still time consuming, particularly when a considerable amount of data had been gathered. To improve the feasibility of the data analysis, a simpler application with pre-defined output of the results, as often used in gait analysis, would be needed. This would facilitate the use of the movement analysis of the drinking task in clinical trials as well as in patient evaluations or treatment planning in clinical settings.

Exploring and validating kinematic variables

Construct validity (dimensionality)

Kinematic analysis can provide an almost unlimited number of variables that could be calculated to analyze a person's motor performance. There is no consensus however, among researchers which kinematic measures are to be preferred for evaluation of the upper extremity performance for people with stroke. The results presented in this thesis demonstrate, however, that when a movement or task is analyzed systematically, clinically useful results can be obtained. Starting with twenty five eligible kinematic variables in Paper I, and then through systematical exploration and testing, the number of variables of interest was reduced to a manageable set of measures. These final measures identified in this thesis may be used as a core-set of kinematic measures for upper extremity tasks after stroke (Table 12). Consequently, these measures can strongly be recommended to be used in descriptive, discriminative or evaluative future studies.

In the current thesis, the Principal Component Analysis (PCA) was applied to kinematic data from the drinking task with intention to extract a manageable number of variables that sufficiently describe the total variance in the original dataset. The PCA has previously predominantly been applied to kinematic data in analysis of gait[118], movement coordination[119], motor control [120] and only recently in movement analysis after stroke.[120-123] In the current thesis, the PCA revealed that in drinking task, the movement performance after stroke can for the most part be described with two main factors. One of them included predominantly the measures of temporal nature (movement time, smoothness, velocity) and the other comprised primarily the spatial movement pattern measures (joint angles, trunk displacement).

Similar distinction between two principal conceptual measure constructs of spatial and temporal parameters in reaching after stroke have been reported earlier.[120,121] Also in motor control research, movement performance in kinematic terms is considered primarily to be organized around joint-angle and endpoint variables.[17] Since the temporal measures, such as movement time, velocity and smoothness are usually obtained from the end-point kinematics (typically a distal marker on the arm); it further confirms that both temporal and spatial aspects are important when upper extremity reaching performance is evaluated with kinematic movement analysis. Interestingly, even in gait analysis, a similar pattern in conceptual measure constructs has been described. Three major components that emerged from the gait analysis in one study were: speed (temporal), symmetry and postural strategy measures (spatial).[118] Findings from previous explorative studies along with the results from this thesis suggest that there is a likely distinction between temporal and spatial upper extremity kinematic measures. This distinction between temporal and spatial aspects along with some examples on the kinematic measures in respective category is illustrated in Figure 12.

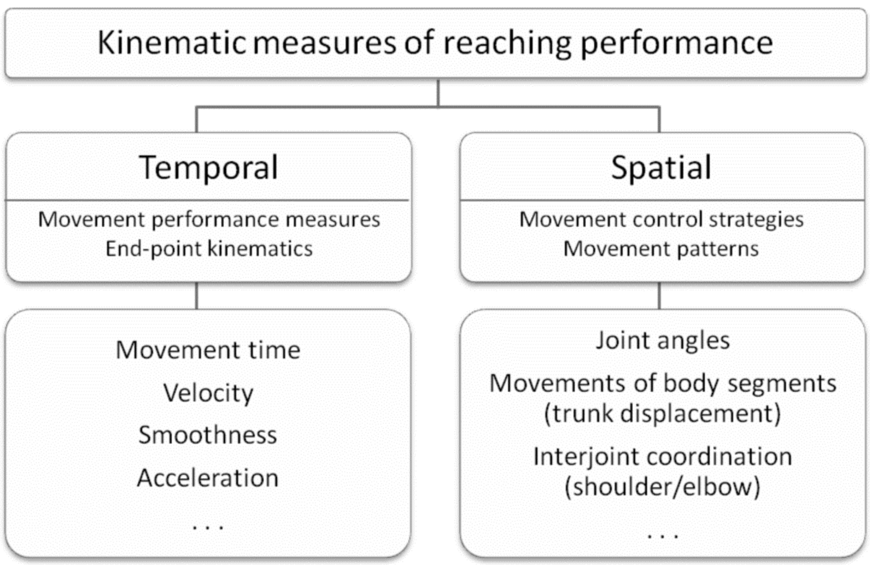

Figure 13. A schematic division between predominantly temporal or spatial kinematic measures commonly used in upper extremity movement analysis after stroke. Note that the list of kinematic measures under respective part is not a comprehensive list.

Discriminative validity

Most of the kinematic studies investigating the upper extremity reaching have demonstrated significant differences between normal (healthy) and impaired (stroke) reaching.[58,62,67,68,70,71,124] Differences between subgroups based on stroke severity have, on the other hand, been reported only in a few studies.[58,71,125] In previous studies, peak velocity has been found to be more effective in discriminating a mild motor impairment and the shoulder abduction in discriminating a moderate motor impairment; movement duration, trunk displacement and elbow extension were discriminative measures for both groups.[58] In another study, the movement smoothness and elbow extension in reaching were discriminating well individuals with moderate impairment after stroke.[125] In the current thesis, the movement time and smoothness discriminated well between all impairment levels; the trunk displacement and shoulder abduction were more effective in discriminating individuals with moderate stroke impairment and the peak velocity along with movement strategy measures differentiated best individuals with mild impairment (Table 12). Consequently, based on these results, it seems that, at least, the movement time and smoothness are fairly good measures to reflect upper extremity function throughout different impairment levels. The compensatory movement patterns, such as shoulder abduction, elbow extension, trunk displacement along with interjoint coordination might be more predominant for the person with moderate impairment; and correspondingly, the peak velocity tends to discriminate better individuals with mild impairment after stroke. In summary, it is likely that certain kinematic measures are more appropriate when the motor function is poor and others when a higher level of function has been reached. More studies are, however needed to verify which kinematic measures are appropriate for different impairment levels after stroke.

Concurrent validity

There are several research papers that have demonstrated significant correlations between kinematic measures and motor impairments after stroke. The most commonly reported clinical assessment, Fugl-Meyer Assessment (FMA-UE) has shown statistically significant correlation with movement time, movement smoothness, peak velocity, trunk displacement, elbow extension and shoulder flexion in reaching tasks in different studies.[57,68,70,74,121,126] Kinematic measures of speed, path ratio and endpoint-error have also shown moderate correlations with Action Research Arm Test (ARAT)[100] and Wolf Motor Function test in people with stroke.[127] In the current thesis, a strong association was found between kinematic measures (movement time, movement smoothness, trunk displacement) and ARAT scores. These kinematic measures explained together 67% of the total variance in ARAT. The associations between kinematics and FMA-UE were lower and the trunk displacement was the only variable that showed significant contribution in the multivariate regression model, explaining 20% of the total variance in FMA-UE.

Based on these results it is likely that the strength of the correlation between different kinematics and clinical scales can vary depending on which specific kinematic measure is analyzed and which specific component of upper extremity function is assessed with a clinical scale. For example, in ARAT, the aspects of task completion within a time limit, performance quality and compensatory movements are assessed. In the FMA-UE, in contrast, the ability to perform isolated movements correct regardless of the time spent is assessed; the time component is assessed only in a subtest of coordination. This could be one possible explanation why temporal kinematic measures showed stronger correlation with ARAT and spatial measures with FMA-UE. Findings from these correlation studies are undoubtedly important, and can, when put together reveal which constructs of the kinematic measures are most likely associated with different aspects of upper extremity function.

Responsiveness and expected change in kinematics – longitudinal validity

There are not many studies that have reported change in kinematic measures during the recovery period after stroke.[58,128] Significant improvements have been noted in measures of movement time, peak velocity, endpoint error and reach path ratio, but changes in angular movements of the shoulder and elbow joint have been found to be smaller.[58,128] In the current study, significant improvements were found in several temporal kinematic measures: movement time, smoothness, peak velocity, time to peak velocity and angular velocity of the elbow joint. Among the spatial measures, trunk displacement alone and not angular movements of the shoulder and elbow joint showed significant improvements during the first three months after stroke. This finding is in concordance with previous studies.[58,128]

Most recently, during the writing process of this thesis (and after submission of the papers included in this thesis), two studies reporting longitudinal changes in kinematic measures early after stroke were noted. These studies reported that the most prominent improvements in kinematic measures (movement time, smoothness, joint angles) during reach-to-grasp tasks occurred within 5-6 weeks poststroke, and relatively little improvement was observed after that.[123,129] This recovery pattern in motor function, with greater gains early after stroke followed by a relative plateau phase, has been described in several previous longitudinal studies using traditional clinical outcomes.[130,131] It is not surprising that also kinematic movement analysis demonstrated a similar recovery pattern, since the spontaneous recovery and rehabilitation input is dominant in this phase. The observed significant improvement in kinematics during the first three months after stroke, as reported in the current thesis, is in line with these longitudinal studies.

Responsiveness of the kinematic measures in people after stroke has been evaluated only in a few studies previously. In these studies, the responsiveness was reported to be high for the movement time and smoothness in a hand-to-mouth task[61] and for the movement time in a reaching task.[76] In these studies, the internal responsiveness statistics, such as effect size or standardized response mean (SRM) were used. These statistics have been criticized since they reflect primarily the magnitude of change in standard deviations, rather than the responsiveness or longitudinal validity of this change.[33,132,133] The internal responsiveness statistics provide nevertheless important information regarding the amount of change among the measures that were used on the same study group. Thus, the results from these responsiveness studies together with results from this thesis indicate that movement time and smoothness in particular, seem to be responsive measures, able to detect changes in upper extremity function over time after stroke.

In this thesis the responsiveness of kinematic measures was evaluated using a mix of different analyses. First, the change over time was calculated in a group where an improvement in upper extremity was expected and clinically verified. Second, the external criterion for a real clinical improvement was defined. Subsequently, the captured change in kinematic measures was tested in relation to the clinical change in upper extremity activity capacity. For this, the ROC-curve analysis and linear regression were used. This approach showed to be constructive and provided interpretable estimates for the expected change in kinematics associated with a real clinical improvement in upper extremity.

Interpretability of kinematic measures

Interpretability has been defined as the degree to which one can assign qualitative meaning to an instruments quantitative score or change in scores.[33] This qualitative meaning is for the most part still unknown for the changes in kinematic measures in stroke research. It remains unclear, whether the detected longitudinal changes in kinematics poststroke are clinically meaningful, and how big should an improvement be when it can signify a clinically important change. In the current thesis, different methods were used in order to establish clinically interpretable and useful estimates for the expected change in a kinematic measure that is associated with a real clinical improvement in upper extremity activity capacity. This approach is new and provides valuable knowledge about the interpretability of the change values in kinematic measures after stroke. In addition, in Paper IV a straightforward interpretation of change values in kinematic measures is provided. The reported regression coefficients (B) can be used to estimate a change in kinematics corresponding to any preferred change in upper extremity function assessed with ARAT.

The reference values, as reported in Paper I and II, for healthy individuals will further facilitate the interpretation of kinematic measures. In the future, a standardization of task and its measures along with appropriate normative data will probably be required for several basic daily tasks. Increased availability of normative and pathologic kinematic data on different tasks would be beneficial for further research and would facilitate potential clinical use.

Limitations

Some specific limitations of the studies included in this thesis have been addressed previously, but some more general limitations are warranted for consideration when interpreting the results of this thesis. First, the study groups were relatively small. For example, in Paper II and III, larger sample size would have been preferable for the statistical analysis of PCA and linear multiple regression. Even though the results from these analyses should be interpreted with care, the main tendencies and trends are expected to be stable even with large sample sizes. This standpoint is supported by the fact that findings from this thesis were in line with other studies in the area and that the same kinematic measures emerged as strongest from different analysis used in Studies II-IV. The sample sizes in general, have been increasing in upper extremity kinematic studies of people with stroke during the last decade, but still only few studies have investigated groups larger than 50 individuals (Appendix).

In Paper I, the test-retest consistency was investigated, and it was sufficient at this initial stage of the study, but a more extensive reliability testing also in individuals with stroke would be needed for the main kinematic variables in the future.

The degrees of freedom and complexity of joint movements in upper extremity is very high. This was also one of the reasons why only the angular movement of shoulder and elbow joint were analyzed and the acromioclavicular and scapulothoracic movements were not considered. This simplification was made with intention to keep the study protocol, set-up and data handling in a manageable scale suitable for clinical use. The single-marker model may have limitations when calculation of joint rotations is in focus. On the other hand there are several studies in which the single-marker model has been shown to be reliable and effective for the analysis of upper extremity tasks.[49,51,52,60,61,71,74]

Further generalization and theoretical integration

Translational and interactive approach between different disciplines and research fields along with clear distinction between recovery and compensation has been suggested to be indispensable when effective rehabilitation strategies are developed.[15,19,134] Objective kinematic movement analysis can provide detailed and relevant information about movement performance and motor compensations which can facilitate the distinction between recovery and compensation after stroke. Development of new technology-based therapies is further pushing forward the integration process between adjacent research fields and the positive effects of this process can already be seen in recent publications.

For instance, in two recent publications, a method to measure and improve upper extremity function in people after stroke combining robot technology, video "gaming" and virtual reality was presented.[135,136] The authors presented a theoretical model for the movement action and its goal integrated with quantitative kinematic evaluation, the ICF model and the concept of "recovery" and "compensation" as earlier presented by the Levin et.al.[19] In their approach, the kinematic features of the upper extremity reaching and grasping were organized into seven categories and described as either an activity level or body function level category. The activity level categories included predominantly the temporal kinematics derived from the end-point measures and the body function level comprised mainly spatial measures of joints and body segments.[135,136] The authors also suggested that recovery in spatial measures would indicate that a pre-morbid movement pattern is used to accomplish a task. On the other hand, the recovery of pre-morbid movement pattern is not required for action completion.[135,136] While this approach seems promising, the theoretical concept and its usefulness remain to be proved in future research.

Considering the current thesis, a number of similarities in findings can be seen with the above described integrated approach. First, the high correlation revealed between the temporal kinematics (movement time and smoothness) and the upper extremity activity capacity (ARAT) in the current thesis confirms that the temporal kinematics might be more closely related to the activity level measurement. Second, the upper extremity impairment on the body function level (FMA-UE) demonstrated the highest correlation with the trunk displacement measure, which confirms the relationships between spatial and body function level action. Third, a clear distinction between temporal and spatial kinematic measures emerged from the explorative factor analysis used on the kinematic measures of the drinking task in people after stroke.

Clinical implications

Regaining upper extremity function is a major challenge in stroke rehabilitation. It is also clear that selection of an assessment method for upper extremity function is crucial and plays a key role when effectiveness of a rehabilitation intervention is evaluated. In clinical settings, in the best case, the upper-extremity function is assessed with traditional clinical observational rating scales, such as Fugl-Meyer Assessment (FMA-UE) or Action Research Arm Test (ARAT). In Sweden, however, in many hospitals and rehabilitation units, general assessment scales are often used for motor function assessments. In general motor scales, the upper extremity scoring items are included into the total score of motor function, which is a clear limitation.

The Action Research Arm Test (ARAT) demonstrated high correlation with objective kinematic measures as reported in this thesis, which indicates that it reflects relatively closely an individual's actual movement performance level. The ARAT has also been shown to have good validity, excellent reliability and high responsiveness after stroke.[37,81,90,92] Thus this assessment scale could be recommended for the upper extremity assessment in clinical praxis in people after stroke.

A strong correlation was found in this thesis between kinematic measures of movement time and smoothness. This indicates that a timed standardized testing of a movement or task will provide indirect information about movement qualities, such as smoothness and movement efficacy. This coupling has a high clinical relevance for upper extremity assessments. Considering the cost, availability and knowledge needed for the kinematic analysis, the standardized timed testing could be a good alternative in the clinical setting in order to obtain indirect information about the quality of movements in clinical evaluation. Parallel can also be drawn to the gait speed that has in earlier studies been shown to be a strong indicator of overall motor performance.[137] Thus it is likely that self selected movement time for example in drinking task can be used to reflect motor performance in general.

In this thesis, clinically relevant and effective kinematic measures characterizing the main aspects of movement performance in a daily activity were identified. Preferably, also in clinical assessments these qualities of movement should be included when upper extremity function and activity is assessed. First, the time component of a movement or task has shown to be important. Second, the movement smoothness, which reflects the movement control and coordination, is essential to observe and record. Third, compensating movement patterns are common after stroke and should be noted as well.

Previous kinematic studies have also shown that experienced physical therapists using a visual analogue scale were capable of making accurate judgments of movement speed, jerkiness and hand path indirectness when observing videotaped movement performance during a grasping task in people with stroke (item 1 from the ARAT).[138]

Kinematic movement analysis provides precise information of movement quality. The qualitative aspects of movement performance are important when distinction between recovery and compensation is in focus. Previous studies have also shown that qualitative feedback (knowledge of performance), compared to the feedback of outcome (knowledge of result) is favorable for recovery of motor patterns.[48]

Kinematic movement analysis provides both quantitative and qualitative results. The obtained measures are objective and not influenced by subjective observer bias or restricted by predefined scores of an ordinal scale. They are sensitive to small specific changes and usually free of ceiling effect. On the other hand, at least in Sweden, very few clinical settings have accessibility to a kinematic movement analysis laboratory and particularly not to an upper extremity analysis routine.

The experiences gained during the data collection for this thesis affirm that when a movement laboratory is located close to the clinical ward and there is a trained clinician who can perform the analysis, the data capture is not more complicated than an assessment with a clinical scale. For increased future clinical use, however, a more practical data handling and a more convenient output report of the results would be required. Some of the described advantages and disadvantages of the kinematic movement analysis present in the upper extremity applications are displayed in Figure 14.

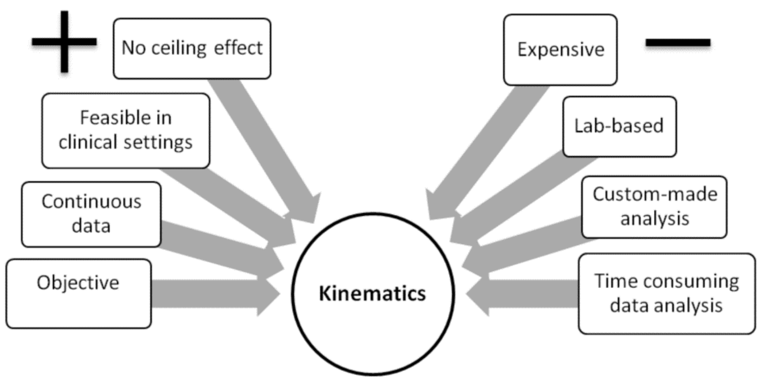

Figure 14. Advantages and disadvantages of the kinematic movement analysis in the upper extremity applications.

Last but not least, common complaints expressed by a person with stroke are often similar to the categories that emerged from the kinematic analysis in this thesis. After a stroke a person often describes that everything takes longer time and they are slow while performing daily activities; they feel clumsy and less smooth in their movements with the affected arm and hand; and they need to compensate and use the unaffected side or entire body in order to accomplish a task.

CONCLUSIONS

- Kinematic analysis of an upper extremity task, such as drinking task, has a great potential to be used as outcome measure in clinical trials or in clinical evaluations when improvements in motor performance are evaluated after stroke. The analysis of basic purposeful tasks from real-life will enhance the ecological validity of the outcome measures derived from the movement analysis.

- This thesis revealed that among others the movement smoothness, movement time and trunk displacement were most effective in discriminating individuals with different functioning level; they were strongly related to the upper extremity activity capacity level; and demonstrated to be effective in detecting a real clinical improvement in upper extremity after stroke.

- Thus these three measures are valid for assessment of upper extremity function and activity after stroke and can be considered as key measures for kinematic movement analysis of upper extremity tasks for people after stroke.

- Knowledge from this thesis facilitates both clinical and movement analysis research and can be valuable in the area of bioengineering when assessment methods for new technology-based devices are developed.

FUTURE CONSIDERATIONS

It is evident that we are standing in front of a paradigm change in neurological rehabilitation. The technology moves rapidly forward and new assessment methods and treatment approaches are constantly developed. The kinematic movement analysis as we know it today will be improved in the future and the specific methods used today will probably be modified and improved. In addition, the knowledge and experience gained from the kinematic movement analysis is highly valuable when new technology-based devices are developed for assessment and training of motor function and activities after stroke.

Some further considerations that have emerged during the progress of this work are listed here:

- More studies are needed to investigate the performance of basic daily tasks with kinematic movement analysis for people with stroke. As many movement characteristics are task-dependent, it is likely that systematic analyses of the appropriate measures would be required for several different basic tasks.

- There is a need to develop and establish better guidelines for the kinematic movement analysis in people with different disabilities. In addition, guidelines with different technical complexity level would be needed in order to target different goals in biomechanical, motor control and clinical research.

- More studies are needed to verify which kinematic measures are appropriate for different impairment levels after stroke. This would facilitate the selection of appropriate kinematics for future clinical trials.

- The work with conceptual measure constructs of kinematic measures in conjunction with clinical assessments should be explored further. This might require that comparisons should be performed also on the subtest or single item level.

- Increased number of longitudinal studies using kinematic movement analysis will be required to enable a more detailed and specific understanding of the recovery pattern after stroke.

- There is an obvious need for additional reliability and responsiveness studies on kinematic measures in upper extremity.

- To improve the clinical use of kinematic movement analysis in the upper-extremity evaluations, a simpler data handling with pre-defined output for the results, as often used in gait analysis, would be needed.

Development of new rehabilitation technologies, such as robotic devices, virtual reality and sensor-based monitoring have further pushed the research in the field of kinematics forward. These technologies, when used in clinical trials or in evaluations of clinical recovery, are also expected to provide qualitative kinematic assessments on an individual's motor performance. Thus further research is necessary to clarify the validity, reliability, responsiveness of the kinematic measures even in those new applications. In addition, the correlation between kinematic assessments and clinical scales in new applications other than motion capture needs to be established.

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APPENDIX

An overview of the clinical research performed in the area of upper extremity kinematic movement analysis in people after stroke. In the left column the working process of the research and the published papers as presented in this thesis is added to the timeline of this summary. The overview is not a comprehensive list, but includes most relevant articles with reference to the current thesis dated from 1990 and forward.

Current thesis	Study	Stroke	n	Movement/task	Measures	Analysis
	Trombly 1992[139]	Chronic	5	Reach-to touch	PV, strategy (T2PV%), NMU	Descriptive Change over time
	Levin 1996[70]	Chronic, spastic (Healthy)	10 (6)	Pointing close, far, ipsilateral, contralateral targets, horizontal plane, self-paced	Path, MT, velocity, path ratio, IJC	Descriptive (context) Comparative (condition) Correlation (spasticity, FMA)
	Trombly 1999[64]	Chronic	14	Reaching with and without a real object	MT, NMU, PV, distance, strategy (T2PV%)	Comparative (context)
	Archambault 1999[67]	Chronic (Healthy)	8 (6)	Pointing ipsilateral, contralateral targets, fast, horizontal plane, trunk still, intentional trunk displacement	MT, TD, NMU, PV, synchronization, error	Descriptive Comparative (context, condition) Correlation (FMA, spasticity)
	Platz 1999[76]	Chronic (Healthy)	29 (20)	Finger tapping; aiming task, dual task	MT, error	Test-retest; responsiveness Comparative (condition)
	Cirstea 2000[68]	Chronic (Healthy)	9 (9)	Pointing contralateral target without vision	MT, PV, path, IJC, path ratio, error, joint angles, TD	Comparative (impairment level) Correlation (FMA, spasticity)
	Wu 2000[66]	Chronic (Healthy)	14 (25)	Reaching with and without object	MT, PV, NMU, strategy (T2PV)	Descriptive Comparative (context)

Current thesis	Study	Stroke	n	Movement/task	Measures	Analysis
	Michaelsen 2001[57]	Chronic (Healthy)	11 (11)	Reach-to-grasp Cone (0.5 and 1 arm length), with and without trunk constraint, midline, self-paced	MT, PV, path, NMU, path ratio, TD, joint angles, IJC	Descriptive (context) Comparative (context, condition Correlation (FMA)
	Levin 2002[56]	Chronic (Healthy)	11 (11)	Reach-to-grasp cone (0.5, 1, 1.3, 2 arm length), midline, self-paced	MT, PV, path, path ration, TD, joint angles, IJC	Descriptive Comparative (context, condition) Correlation (FMA)
Planning Study I 2003	Cirstea 2003[71]	Chronic (Healthy)	18 (10)	Pointing contralateral target, accurate, fast	MT, PV, distance, path ratio, error, angular velocity, joint angles, TD, oscillation, coordination	Descriptive Comparative (condition) Correlation (FMA, spasticity)
	Roby-Brami 2003[58]	Subacute, chronic; (Healthy)	15 (7)	Reach-to-grasp Cone, self-paced, beyond reach	MT, PV, joint angles, TD	Descriptive Comparative (impairment level/healthy) Change over time (n=9)
Data collection Study I, 2004	Zakowski 2004[73]	Chronic (Healthy)	18 (18)	Reach-to-touch 2 targets, isolated joint movements, fast, 1st part of reach	PV, error, path ratio, joint angles, individuation index	Descriptive (context) Correlation (strength, spasticity, sensation)
Paper I (n=20, healthy) 2006	Michaelsen 2006[50] RCT	Chronic	15/15	Reach-to-grasp cone, 80% arm's length, midline, self-paced, without lifting	TD, elbow extension (PV, NMU, path ratio)	Comparative (effect of trunk restraint/task training, mild/severe) Correlation (TEMPA)
	Wagner 2006[72]	Acute (Healthy)	46 (10)	Reach-to touch fast, constrained trunk, 90% arm's length, 1st phase of reaching	PV, error, path ratio	Descriptive Correlation (sensorimotor impairments: AROM, strength, individuation, sensation, spasticity, pain)

Current thesis	Study	Stroke	n	Movement/task	Measures	Analysis
	Chang 2006[125]	Subacute, chronic	20	Reaching Toward cup without grasp, unilateral, bilateral, horizontal, fast, weights	MT, PV, strategy (T2PVel), NMU, normalized jerk, joint angles, TD	Descriptive Comparative (context)
	Messier 2006[60]	Chronic (Healthy)	15 (13)	Transportation cone, unilateral, bilateral	Joint angles, TD	Comparative (context, condition, arm)
	Cirstea 2007[48] RCT	Chronic (Healthy)	14+14 (5)	Pointing contralateral target without vision, fast, feedback + ipsilateral transfer task	Joint angles, IJC, TD	Comparative (context, condition) Correlation (clinical change)
	Wagner 2007[128] Longitudinal	Acute to subacute (Healthy)	39 (10)	Reach-to touch fast, constrained trunk, 90% arm's length, 1st phase of reaching	PV, error, path ratio, individuation	Descriptive (change) Relationships (impairments)
	van Vliet 2007[62]	Chronic (Healthy)	12 (12)	Reach-to-grasp, take a sip small, large cup filled with water, , self-paced, fast, reaching phase	MT, PV, strategy (T2PV) acceleration, grasp aperture	Descriptive (context, condition)
	Lin 2007[49] RCT	Chronic	15+17	Reach-to-grasp-to-lift up can, self-paced, constrained trunk	RT, normalized MT, NMU strategy (T2PV%), grip aperture	Descriptive Comparative (effect of CIMT)
Data collection Study II 2008	Wagner 2008[75] Test-retest MDC	Chronic	14	Targeting 110% arm length, stabilized trunk, self-paced, fast, low, high target	MT, PV, strategy (T2PV), path ratio, error, distance, joint angles, IJC, NMU	Test-retest (4week between), MDC
	Caimmi 2008[61]	Chronic (Healthy)	8 (8)	Reach- to-target Hand-to-mouth still trunk and head, self-paced	MT, joint angles, PV, angular velocity, acceleration, normalized jerk	Comparative (CIMT) Test-retest (healthy) Responsiveness

Current thesis	Study	Stroke	n	Movement/task	Measures	Analysis
Data collection Study III, IV, 2009-2011	Woodbury 2009[51] RCT	Chronic (Healthy)	6+5 (5)	Reach-to touch target Midline,80% arm's length	NMU, path ratio, joint angles, TD, IJC	Comparative (modified CIMT, trunk restriction, healthy)
	Subrimanian 2010[74]	Chronic	44* 42*	Pointing* Reach-to-grasp*	TD, joint angles	Correlation (FMA) Discriminative (FMA)
Paper II (n=19/19, stroke/ healthy) 2011	Patterson 2011[59]	Chronic (Healthy)	18 (9)	Reach-to touch target Midline, 80% arm's length, self-paced/fast Reach-to-Grasp Cone, small, large, self-paced	MT, PV, path ratio, TD, grasp aperture	Test-retest
Paper III (n=30) 2012	Wu 2011[52] RCT	Chronic	22+22+22	Reach-to-target desk bell, Open a drawer, bilateral task, constrained trunk	MT, NMU, PV, strategy (T2PV%)	Comparative (distributed CIMT, bilateral training, control group)
Paper IV (n=51) 2013	Wu 2013[53] RCT	Chronic	16+17	Reach-to-target desk bell, 90% arm's length, constrained trunk, self-paced	RA, MT, distance, joint angles, IJC	Comparative (mirror therapy, control group)

Abbreviations: PV, peak velocity; T2PV%, percentage of time to peak velocity; NMU, number of movement units; MPT, movement trajectory; MT, movement time; HPR, hand path ratio; IJC, interjoint coordination; TD, trunk displacement; ME, movement error; RA, reaction time; FMA, Fugl-Meyer Assessment; TEMPA, Upper Extremity Performance Test for Elderly; AROM, active range of motion; CIMT, constrained induced movement therapy; MDC, minimal detectable change; RCT, randomized control study; * pooled data from: Cirstea 2007[48], Michaelsen 2006[50]