Clinical and kinematic assessments of upper limb function in persons with post-stroke symptoms

Gudrun Johansson
To my family
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Abstract

**Background** Stroke is a common and multifaceted disease that often involves motor deficits in the upper limb. To be able to evaluate motor recovery and possible use of motor compensation after stroke, quantitative and qualitative movement assessment is needed. Existing clinical scales are usually based on crude ratings of motor performance that cannot detect subtle motor deficits or compensatory strategies. Optoelectronic motion registration provides an objective quantification of motor performance that is highly detailed and appropriate when evaluating upper limb recovery after stroke. This method can also be used to investigate the measurement properties of existing clinical scales. The overall aim of the thesis was to evaluate clinical and kinematic assessments of upper limb function in persons post-stroke. A second aim was to further develop existing test procedures and assessments of upper limb function after stroke.

**Methods** The thesis involves four studies; one conducted in a clinical setting (Study I) and the others took place in a motion analysis laboratory (Studies II-IV). In total, 76 persons post-stroke and 41 non-disabled control persons participated. To investigate the reliability and validity of the Motor Evaluation Scale of Upper Extremity in Stroke patients (MESUPES), 42 persons post-stroke were assessed independently by two physiotherapists selected from a group of four (Study I). A comprehensive set of statistical analyses was used to establish absolute and relative reliability of the MESUPES. The concurrent validity was studied by comparing the MESUPES with a criterion measure (gold standard) that was taken at the same time. Study II investigated deviations in the arm swing during gait in 25 persons post-stroke compared to 25 controls by applying the newly developed Arm Posture Score (APS4). This is a comprehensive kinematic index based on four movement variables; shoulder, elbow and wrist flexion-extension and shoulder abduction-adduction. The effect of adding shoulder and forearm rotation to the APS4, referred to as APS6, was also investigated. Study III evaluated the discriminative and concurrent validity of the Finger-to-Nose test (FNT), which is a coordination test, in 33 persons post-stroke and 41 controls by 3D motion analysis and clinical assessments. The fourth study investigated the discriminative and concurrent validity of the Standardised Nine Hole Peg Test (SNHPT), which is a dexterity test, in 30 persons post-stroke and 41 controls, in a similar way as in Study III.

**Results** The MESUPES showed a high inter-rater reliability and the minimal detectable change ranged from 5 to 8 (maximum score 58) for a confidence level of 80% and 95%. Although the correlation between
MESUPES and the Modified Motor Assessment Scale was high, further research is needed to confirm the concurrent validity. Both the original and the modified APS indices were able to distinguish between the affected and non-affected arms, as well as between the affected arm and the non-dominant arm of the controls. The total movement time (TMT) to perform the FNT was able to distinguish persons post-stroke from controls, at least at a group level. Movement smoothness, accuracy and compensation, which were provided using kinematic analysis, were the most discriminative variables. Smoothness had the highest correlation with the TMT to perform the FNT and had the greatest association with the variance of the TMT for the FNT. For the S-NHPT, movement times, smoothness and compensation, which were provided using kinematic analysis, were able to discriminate between the stroke group and the control group. Persons with post-stroke symptoms spent considerably more time in the grasp-related parts of the task compared to controls. Smoothness and upper limb impairments had the highest correlation with the S-NHPT.

**Conclusion** This thesis shows that the MESUPES is a reliable assessment of upper limb movement quality after stroke. The estimates of minimal detectable change of the MESUPES provide useful information to clinicians of the true change in an individual patient over time or after intervention. Another finding of this thesis is that kinematic analysis, obtained by optoelectronic motion registration, provides unique information about upper limb function after stroke, not least in persons with mild post-stroke impairments. The APS, for instance, discriminates deviation of arm swing during gait in persons with stroke to that of non-disabled persons. Such subtle deviations are not possible to quantify by the human eye. For health facilities with access to gait analysis laboratories, the APS can be used for patients over time and after intervention. Results from the kinematic analysis also revealed that the timed FNT does not have sufficient discriminative validity at an individual level. The timed FNT reflects speed-related aspects of pointing movements such as smoothness and length of the deceleration phase but should not be used as an overall measure of upper limb coordination after stroke. The timed S-NHPT demonstrates sufficient discriminative validity and reflects smoothness and upper limb impairments. For both the FNT and S-NHPT, kinematic analysis revealed that the clinical outcomes of those tests (time of performance) do not adequately detect qualitative aspects of the upper limb movements after stroke such as possible compensatory movements. Therefore, clinical assessments that capture qualitative aspects of upper limb movements would improve the assessment of upper limb coordination and dexterity after stroke.
Svensk sammanfattning

Avhandlingstitel: Klinisk och kinematisk utvärdering av hand- och armfunktion hos personer med symtom efter stroke.


I delstudie I deltog 42 patienter med stroke. Två sjukgymnaster bedömde, oberoende varandra, hand- och armfunktion hos patienterna med hjälp av det översatta testet Motor Evaluation Scale of Upper Extremity in Stroke patients (MESUPES). Den ena bedömare var ansvarig för patienten och den andra bedömare lottades bland de övriga tre ur en grupp av totalt fyra tillgängliga fysioterapeuter (tidigare yrkestitel var sjukgymnaster). Ett flertal
statistiska analyser användes för att utvärdera reliabiliteten hos MESUPES. Samstämmigheten var god mellan olika sjukgymnaster, vilket indikerade att MESUPES hade en hög interbedömarreliabilitet. Beräkningar visade att det behövdes 8 poängs skillnad i MESUPES för att vara 95 % säker på en sann skillnad hos en individuell patient. Även om korrelationen mellan MESUPES and ett annat kliniskt mätinstrument (kriterievariabel) var god så behövs fler studier för att säkerställa samtidig validitet.

Tre-dimensionell datoriserad gånganalys har traditionellt sett fokuserat på nedre kroppshalva. Den komplexa analysen av gångdata har gjorts mer hanterbar genom framtagna index som summerar avvikelser i rörelsemönstret för nedre extremitet. På senare tid har ett liknande index tagits fram för armpendling vid gång, det så kallade Arm Posture Score (APS), som summerar avvikelser i armrörelser och som använts för att studera armpendling under gång hos barn med cerebral pares. Syftet i Studie II var att undersöka om APS var lämpligt för en stroke population. APS består av fyra röelsevariabler (flexion/extension i axel-, armbågs- och handled samt abduktion/adduktion i axelled), i denna avhandling refererad till såsom APS₄. Ett annat syfte var att utvärdera effekten av att lägga till två variabler (axel inåt/utåtrotation och pronation/supination), refererad till som APS₆. Resultat baserat på data från 25 personer som haft stroke och 25 ålders- och könsmatchade kontrollpersoner visade att både APS₄ och APS₆ kunde skilja på avvikande och normal armpendling efter stroke. Även om APS₆ inte visade högre diskriminativ validitet än APS₄ för denna strokegrupp, så kan APS6 ge viktig information för patientgrupper där armrotation är påverkad. Ytterligare studier behöver göras för att utvärdera detta.

I delstudie III och IV undersöktes validitet hos två etablerade kliniska test nämligen Finger-to-Nose test (FNT) och Nine Hole Peg test, varav det första används för att mäta koordination och det andra för att mäta finmotorik. En standardisering av Nine Hole Peg test (S-NHPT) gjordes för att att erhålla reliabla och jämförbara rörelse banor. Totala rörelsetiden för att utföra FNT och S-NHPT (dvs. klinisk utfallsvariabel), kinematiska variabler och andra kliniska mått jämförda mellan grupperna (diskriminativ validitet) och inom stroke gruppen (samtidig validitet). Resultat baserat på 33 personer som haft stroke och 41 kontroller visade att den diskriminativa validiteten för tidsbaserat FNT inte var tillräcklig på individnivå. Tid att utföra FNT efter stroke var mest korrelerat med hastighetsberoende variabler. Tid att utföra S-NHPT baserat på 28 personer som haft stroke och 41 kontroller visade tillräcklig diskriminativ validitet. Kinematisk analys visade att personer som haft stroke ägnade mer tid till att greppa och släppa pinnarna jämfört med kontrollpersonerna. Inom stroke gruppen, var tid att utföra S-NHPT mest
korrelerat med hastighetsberoende variabler och funktionsnedsättningar i hand och arm. Kvalitativa aspekter av rörelser efter stroke avspeglades inte tillräckligt i tidsvariabeln varken för FNT eller för S-NHPT.

Sammanfattningsvis visar denna avhandling på att MESUPES är ett reliabelt kliniskt test för att utvärdera rörelsekvalitet i hand- och armfunktion efter stroke. MESUPES kräver ingen speciell lokal eller utrustning för att användas vilket är en fördel med tanke på att rehabilitering efter stroke sker allt mer utanför sjukhuset. För att kunna utreda om en funktionell förbättring efter stroke beror på återtagande av tidigare rörelsemönster (‘true motor recovery’) eller nya rörelsemönster (motor compensation), behövs mätmetoder som mäter kvalitativa aspekter både på funktions- och aktivitetsnivå. Detta kan göras med kliniska test som mäter kvalitativa aspekter av rörelser som t.ex. MESUPES och/eller med instrumentell rörelseanalys. Denna avhandling visar att kinematisk analys i form av optoelektronisk kamera registrering av rörelser tillför viktig och unik information om motorisk återhämtning efter stroke, inte minst hos personer med små funktionsnedsättningar. Uppbyggnad av fler rörelselab och mobila rörelsesystem möjliggör att index som t.ex. APS kan användas för att utvärdera avvikelser av armpendling vid gång efter stroke över tid eller efter specifik behandling. Denna teknik kan även användas för att utvärdera andra funktionella armrörelser efter stroke, som t.ex. sittande med eller utan hantering av föremål. Oavsett metod att inhämta rörelsedata, har fysioterapeuter en viktig roll i teamet att tolka kvantitativ och kvalitativ rörelsedata och översätta det till klinisk nytta för patienten.
## Abbreviations

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<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tr>
<td>ADL</td>
<td>Activities of daily living</td>
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<tr>
<td>ANOVA</td>
<td>Analysis of variance</td>
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<td>APS</td>
<td>Arm Posture Score</td>
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<td>ARAT</td>
<td>Action Research Arm Test</td>
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<td>BMI</td>
<td>Body mass index</td>
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<td>CI</td>
<td>Confidence interval</td>
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<td>CIMT</td>
<td>Constraint-induced movement therapy</td>
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<td>EQ-5D</td>
<td>Euroqol 5 Dimensions self–report questionnaire</td>
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<td>FMA-UE</td>
<td>Fugl-Meyer Assessment scale for the upper extremity</td>
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<td>FNT</td>
<td>Finger-to-Nose Test</td>
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<td>GPS</td>
<td>Gait Profile Score</td>
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<tr>
<td>GVS</td>
<td>Gait Variable Score</td>
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<td>GVS&lt;sub&gt;ARM&lt;/sub&gt;</td>
<td>Gait Variable Scores for the upper limb</td>
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<tr>
<td>IADL</td>
<td>Instrumental activities of daily living</td>
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<td>ICC</td>
<td>Interclass Correlation Coefficients</td>
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<td>ICF</td>
<td>International Classification of Functioning, Disability and Health</td>
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<td>IJC</td>
<td>Interjoint coordination</td>
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<tr>
<td>IQR</td>
<td>Interquartile range</td>
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<td>MAS</td>
<td>Modified Ashworth Scale</td>
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<tr>
<td>MDC</td>
<td>Minimal detectable change</td>
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<tr>
<td>MESUPES</td>
<td>Motor Evaluation Scale for Upper Extremity in Stroke patients</td>
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<td>MMAS-UE</td>
<td>Modified Motor Assessment Scale, upper extremity part</td>
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<tr>
<td>NHPT</td>
<td>Nine Hole Peg Test</td>
</tr>
<tr>
<td>NMU</td>
<td>Number of movement units</td>
</tr>
<tr>
<td>PS</td>
<td>Peak speed</td>
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<td>RCT</td>
<td>Randomized controlled trial</td>
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<td>RMSD</td>
<td>Root mean square difference</td>
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<tr>
<td>ROM</td>
<td>Range of motion</td>
</tr>
<tr>
<td>SD&lt;sub&gt;diff&lt;/sub&gt;</td>
<td>Standard deviation of the difference</td>
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<tr>
<td>SE</td>
<td>Standard error</td>
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<tr>
<td>SEM</td>
<td>Standard error of measurement</td>
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<tr>
<td>S-NHPT</td>
<td>Standardised Nine Hole Peg Test</td>
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<tr>
<td>TIA</td>
<td>Transient ischemic attacks</td>
</tr>
<tr>
<td>TMT</td>
<td>Total movement time</td>
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<td>TPS</td>
<td>Time to Peak speed</td>
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<tr>
<td>UE</td>
<td>Upper extremity</td>
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<tr>
<td>WHO</td>
<td>World Health Organization</td>
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<td>WMFT</td>
<td>Wolf Motor Function Test</td>
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**Definitions**

<table>
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<th>Term</th>
<th>Definition</th>
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<tr>
<td>Coordinated movements</td>
<td>In this thesis, this is referred to as smooth, efficient and accurate movements based on correct sequencing, timing and grading of the activation of multiple muscle groups (1).</td>
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<tr>
<td>Minimal detectable change</td>
<td>Amount of change in a variable that must be achieved to reflect true difference; the smallest amount of change that passes the threshold of error (2).</td>
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<tr>
<td>Motor control</td>
<td>Area of science exploring natural laws that define how the nervous system interacts with other body parts and the environment to produce purposeful, coordinated movements (3).</td>
</tr>
<tr>
<td>Quality of movement</td>
<td>In this thesis, this concept is referred to as how well a movement is performed, and can be considered as the way individuals without any underlying illness or disorder perform a movement. This is normally the most efficient way as possible (4).</td>
</tr>
<tr>
<td>Reliability</td>
<td>The degree of consistency with which an instrument or rater measures a variable (2). The agreement among multiple raters (inter-rater reliability) was investigated in this thesis.</td>
</tr>
<tr>
<td>Validity</td>
<td>The extent which an instrument actually measures what it is intended to measure (2). In this thesis, the degree to which an instrument distinguish pathological movement performance from that of healthy movement performance (discriminative validity), and the degree to which an instrument agrees with other instruments that are measuring the same factors (concurrent validity) were investigated.</td>
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Original Papers

This thesis is based on the following papers, referred to in the text by their Roman numerals I-IV


III  Johansson GM, Grip H, Levin MF and Häger CK. Validity of the timed Finger-to-Nose test as a measure of upper limb coordination in persons post-stroke – a kinematic analysis. (Manuscript)

IV  Johansson GM, Grip H, and Häger CK. Validation and standardisation of the Nine Hole Peg Test for kinematic quantification in persons post-stroke. (Manuscript)

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Preface

In my clinical practice as a physiotherapist, I use clinical tests that are considered valid and reliable when assessing upper limb function in patients who have had a stroke. My impression is that some established tests are not sensitive enough to detect mild motor impairments or small, but meaningful, changes of motor recovery after stroke. Further, I have felt that most of the tests only focus on task accomplishment (e.g. can or cannot, time of excursion, numbers of repetitions) without considering possible use of compensatory movements. As a result of my clinical experience with patients with subacute and chronic stroke, I have come to the opinion that compensation should not be neglected, especially not in young patients who will live many years after the stroke occurs. In the short term, compensation may result in earlier independence for the patient, but in the long term compensation may lead to negative consequences for both the affected and less-affected side of the body. Thus, compensation is important to consider when assessing upper limb performance after stroke. As I believed that there were too few clinical tests that used such a qualitative approach, I searched for new tests in the literature. That search led to the first study of this thesis. A couple of years later I had the opportunity to attend my first course in instrumental gait analysis. It was fascinating to achieve detailed information about motor performance that was not possible to estimate with the human eye or clinician-rated assessments. I wanted to study how information from optoelectronic motion registration could be transferred into clinical scenarios and in the development of assessments. Due to the lack of studies that included clinical assessments together with kinematic assessments of upper limb function after stroke, the idea for this project was born.
Introduction

Stroke is a worldwide disease that can affect motor, sensory, perceptual or cognitive functions and thereby lead to various consequences for the individual, family and healthcare system. This thesis focuses on methods to assess and quantify motor function of the upper limb after stroke. The main objective was to evaluate upper limb function in adults post-stroke, by use of clinical and detailed kinematic assessments. Different measurement properties were investigated in the four studies. The first study took place in a clinical setting while the remaining three studies were performed in a motion analysis laboratory. The three latter studies also included assessments of non-disabled participants.

The introduction to this thesis will provide the reader with a background of studies on motor function of the upper limb. At first, a brief description of stroke is presented. This is followed by a description of motor dysfunction of the upper limb after stroke. Then the physiotherapy interventions and theories behind them are presented. Finally, a description is given of different assessments and relevant measurement properties.

Stroke

A stroke is caused by a disruption of the blood supply to the brain that leads to damage of brain tissue. According to the World Health Organization (WHO) stroke is clinically defined as an “acute neurologic dysfunction of vascular origin with sudden (within seconds) or at least rapid (within hours) occurrence of symptoms and signs corresponding to the involvement of focal areas of the brain” (5). Stroke is a generic term for brain infarction (~85%), intracerebral hemorrhage (~10%) and subarachnoid hemorrhage (~5%). Stroke is often preceded by transient ischemic attacks (TIA) where symptoms appear and last less than 24 hours before disappearing (6).

In Western countries, stroke is the third most common cause of death and the most common cause of neurological disability in adult age (7, 8). During the last decades, stroke incidence in high-income countries has decreased while the incidence rates in low to middle income countries have increased (9). In Sweden, about 25 000 persons suffer a stroke each year (6), and the annual total cost of stroke care is approximately 1.5 billion Euros (10). The majority of those who suffer a stroke (91 % in 2013) receive care at a stroke unit, and the average length of stay in an acute hospital is 12 days (6). Early supported discharge is most developed in the county council of Västerbotten (32% compared to the national average of 15% in 2012). The mean age for having a stroke in Sweden in 2013 was 76 years (73 years for men and 78
years for women). Although stroke incidence increases with age, about 20 % of those who suffer a stroke are 65 years of age or younger. The total amount of TIA in Sweden in 2013 was extrapolated to approximately 10 000 persons (6).

**Upper limb function after stroke**

After stroke, the impaired motor control of the upper limb will affect both fine and gross motor skills in daily activities. Fine motor skills are used in activities such as eating, dressing, grooming and handwriting whereas gross motor skills are used in crawling, walking, balance reactions and protective reactions (1). The most recognized impairment caused by stroke is motor impairment, usually involving the face, upper limb, lower limb, exclusively or in various combinations (11, 12). Motor impairments are often demonstrated as muscle weakness, spasticity, abnormal synergies and coactivation, of which muscle weakness is the most prominent (1, 13). Also, deficits of sensory, perceptual and cognitive functions may influence upper limb movement performances (1). Depending on the type and degree of upper limb impairments, many activities such as personal care, work, hobbies, gestures, and interpersonal relationships may be limited.

The prevalence of impaired upper limb function differ between studies worldwide, probably due to different stroke care, stroke populations, study settings, and outcome measures. In the acute phase, approximately 70-80% of the patients have impaired upper limb function after stroke (14, 15). In the chronic phase, the paretic upper limb remains without function in 30-66% of all stroke survivors, whereas only 5-20% demonstrate full functional recovery (16). In Sweden, recent studies have presented similar or somewhat lower prevalence of upper limb impairments (17, 18). Persson and co-workers found that 308 (48%) of 642 patients had impaired arm and hand function within 72 hours after stroke onset (17). In a prospective study of 66 patients by Welmer et al., 70% had limited fine hand use in the first week, 41% at 3 months and 45% at 18 months (18).

According to a recent review, 40-80% of persons post-stroke were able to walk independently at the chronic stage (19). Arm swing was not addressed in that review. Although recovery of gait is a major goal in stroke rehabilitation (19, 20) and human gait involves rhythmic reciprocal arm swing, the prevalence of impaired arm swing after stroke is rarely reported in the literature. One explanation could be that stroke-specific outcome measures do not take account of arm swing during gait, whether they assess motor functions for the whole body (21-24) or motor functions specific for the upper limb (4, 25, 26). This is probably because the relevance of arm
swing during gait has not been consistent among authors (27-30), and thereby not regularly included as an outcome measure.

Functional status after stroke, including upper limb function, may also be reported according to the International Classification of Functioning, Disability and Health (ICF) (31). The ICF framework was approved by the WHO in 2001 as an international standard to describe and measure health and disability. This comprehensive multidimensional framework has a biopsychosocial view of functioning and disability that consists of two major parts, each of which has two components. The first part includes Body Functions/Structures and Activities/Participation, while the second part includes contextual factors as Environmental factors and Personal factors. The interaction between the ICF components along with examples of functioning and contextual factors are presented in Figure 1.

**Figure 1.** Interactions between the components of ICF along with examples of functioning and contextual factors. Adapted from: World Health Organization (WHO). International Classification of Functioning, Disability and Health: ICF. Geneva: WHO; 2001.
Each component consists of various domains, categories and subcategories, which are the units of classification (codes). The ICF codes are only complete with the presence of a qualifier, which reflects the magnitude of functioning or disability, or the extent to which an environmental factor is a facilitator or barrier. The domains of Activities/Participation consists of two qualifiers; Capacity and Performance. Capacity describes an individual’s ability to execute a task or an action in a standardised environment while Performance describes what an individual does in his or her current environment (31). In other words, Capacity reflects what a person can do and Performance reflect what a person actually does (32). To improve the use of ICF, specific category-lists (i.e. ICF core sets) have been developed for different diseases including stroke. Recent studies from Sweden and Brazil, using the ICF core set for stroke, have reported divergent amounts of disability in the chronic stage (13, 33). The relatively large differences in results of the two studies may be explained by different times of stroke onset and stroke care in each country. In Sweden, 89 stroke survivors reported impairments in several Body Function categories as muscle endurance (79%), gait pattern (75%), muscle power (61%) and control of voluntary movements (44%) three months after stroke. In addition, the 89 Swedish stroke survivors reported limitations in several Activity categories as walking (78%), doing household (50%), fine hand use (46%) and hand and arm use (38%) three months after stroke (13).

Physiotherapy for persons post-stroke
As motor impairment is the most common and widely recognized impairment caused by stroke (11), it is not surprising that physiotherapy is one of the key disciplines in stroke rehabilitation. Since the mid-1900s there has been a mutual development of clinical practice and scientific theory that has influenced the content of physiotherapy (1). The increasing evidence of physiotherapy efficacy has endorsed its central role in interdisciplinary stroke rehabilitation (34).

Theories underlying clinical practice
Before the 1960s, it was believed that the adult CNS was a static structure that had no ability to change structure and function. The patients with neurological dysfunction were treated with orthopaedic approaches that consisted of muscle reeducation and compensation with the non-paretic side (1, 35). These approaches were beneficial for persons with polio but less successful for patients with upper motor neuron lesions such as stroke.

In the 1950s and 1960s, neurotherapeutic facilitation approaches were developed to enhance recovery of the paretic side though techniques designed to facilitate and/or inhibit different movement patterns. These
approaches were mainly based on reflex and hierarchical theories of motor control (1), where the physiotherapist was superior to the patient, who became a relatively passive recipient (35). One approach was the Brunnstrom’s approach, developed in USA by the Swedish physiotherapist Signe Brunnström (36). This approach involved temporal sequenced stages of motor recovery and emphasised development and activation of pathological synergies in order to obtain normal voluntary movements. The well-known Fugl-Meyer Assessment Scale (FMA) is primarily developed from the work of Brunnström (21). The FMA is included in three studies of this thesis. Other treatment approaches from this period are the Bobath approach (37) and the Proprioceptive neuromuscular facilitation (PNF) approach (38).

Since the 1980s, neurological physiotherapy has been developed based on research within medical science, neuroscience, exercise physiology, biomechanics, rehabilitation science and other relevant areas (1, 35). The view of recovery after stroke has progressively changed as studies began to show that the adult CNS retains a much higher capacity for plasticity and reorganization than earlier believed (1). In parallel, newer clinical approaches have been introduced as the motor learning approach, systems approach and task-oriented approach, which all stress active patient involvement (1, 35). Carr and Shepherd developed the Motor relearning programme for stroke that consists of stepwise training of movement components, subsequently functional tasks and activities of daily living (39). Another approach is the Perfetti method, which involves sensorimotor techniques that aim to regain quality of movement within motor recovery in persons post-stroke (40). The Motor Evaluation Scale of Upper Extremity in Stroke patients (MESUPES) (4), a new assessment tool that purportedly assess quality of movement, is evaluated in the first study of this thesis. The MESUPES originates from Perfetti and co-workers (4, 41). Shumway-Cook and Woollacott advocate a task-oriented approach based on a systems theory that incorporates parts of other theories of motor control (1). The task-oriented approach assumes that “movement arises from multiple processes, including (a) perceptual, cognitive and motor processes within the individual, and (b) interactions between the individual, the task, and the environment” (1). The patient acts as a problem solver during functional tasks where various ways to successfully solve the task are encouraged. The task-oriented approach has had a major impact in modern neurological physiotherapy and so thus even in stroke rehabilitation.

During the last decade, the ICF framework has become more and more integrated in different arenas of physiotherapy such as education, research and clinical practice. It appears that the ICF is a useful tool to understand,
communicate and evaluate stroke recovery. In a recent review, different mechanisms of stroke recovery were related to the ICF components Body Functions and Activities (42). Although the knowledge of motor recovery after stroke has increased during the last decades, the underlying mechanisms and processes are still not fully understood. It has been proposed that recovery after stroke is influenced by several non-learning-dependent (spontaneous) and learning-dependent mechanisms, and that recovery may occur via restitution, substitution, or compensation (11, 42). In 2009, Levin and colleagues proposed definitions of motor recovery and motor compensation according to the ICF framework (43). They defined motor recovery within Body Functions/Structures as a restoration of ability to perform movement in the same way as before the injury, whereas motor compensation is performing an old movement in a new way. Within the component Activities, motor recovery was defined as a successful task accomplishment using body parts typically used by nondisabled persons while motor compensation was defined as successful task accomplishment using alternative body parts (43). Since then, several researchers have referred to these definitions, in one way or another (42, 44-46).

**Specific treatments to regain upper limb function after stroke**

The current evidence regarding effective interventions of upper limb recovery is mainly based on patients with chronic stroke due to the lack of proper randomized controlled trial (RCT) studies within the first three months after stroke (42). Reviews have reported several interventions for motor recovery after stroke that have beneficial effects on upper limb function (11, 34, 47), at least within the selected populations that have been studied and based on the outcome measures that have been used. These interventions include constraint-induced movement therapy (CIMT), electromyographic biofeedback, mental practice with motor imagery, mirror therapy, robotics, repetitive task training, and electrostimulation. These interventions seem to have the most effect on arm function but less on hand function (11). There is also evidence that unilateral arm training is more beneficial than bilateral arm training for improving upper limb function and ADLs (47). In clinical practice, physiotherapists may use a single approach or a combination of various approaches (35). The general recommendations for stroke rehabilitation today seem to be that physiotherapists should focus on high-intensity, repetitive task-specific practice with feedback on performance (11), and not be limited to a single ‘named’ approach (35). However, task-specific practice may not be beneficial for all persons post-stroke. In fact, it has been demonstrated that persons with mildly impaired upper limb function require strengthening exercises instead of task-related training to restore function (48). It has also been shown that functional task practice may increase compensatory movements to improve upper limb
function while strengthening exercises lead to more normal movement patterns (49). It is clear that no individual treatment for motor recovery is likely to be appropriate for every patient.

In clinical practice, there has been little focus on regaining arm swing during gait after stroke. There are several explanations why persons post-stroke have received less training of their upper limbs than the lower limbs during walking. Gait rehabilitation usually starts early after stroke, even though the upper limb is in a flaccid period (28). This is because recovery of walking is a high priority in stroke rehabilitation and that upright bipedal walking does not require full motor recovery of the lower limb (19). Even if the upper limb is gradually recovering, slow gait speed and spasticity may reduce the opportunities for persons post-stroke to perform reciprocal arm swing (50). The upper limbs may sometimes for safety reasons be holding on to walking aids and thus have less possibility to swing freely. Although the therapeutic value of arm swinging is not fully confirmed, recent research has emphasized that arm movements should be addressed during gait rehabilitation after stroke (29, 50, 51). This may be done by treatment approaches such as auditory rhythms during gait (51), verbal instructions during gait (51, 52), sliding treadmill handrails (29), and botulinum toxin injections into spastic upper limb muscles (53).

Measuring upper limb function after stroke
There are several factors that should be considered when choosing a measure of upper limb function after stroke. Barak and Duncan have presented a three-dimensional model for functional assessment after stroke that includes: i) levels of assessments (impairment, activity, participation, ii) domains of assessment (motor, cognitive, emotional and social functions), and iii) type of measurement (discriminative, predictive, evaluative) (54). This model can be helpful for clinicians and researchers to choose an appropriate test. Further, the level of upper limb impairments must be considered to avoid floor or ceiling effects. Floor effects emerge when a test is too difficult for the stroke population while ceiling effects occur when a test is too easy; thus, scores are too low or too high, respectively (1). The equipment and time to administer the test must also be considered. Finally, the outcome measures selected should have been tested in individuals post-stroke and have sound psychometric properties (54).

Clinical assessments
Clinical tests of upper limb function may involve manual assessments, observational assessments, interviews and questionnaires. Some tests may also need some equipment (e.g. stopwatch, goniometer, and dynamometer) or include different objects to reach for, grasp, manipulate, transfer and
release. Many of the tests of upper limb function after stroke are performed supine or seated. Common clinical tests used in stroke rehabilitation have been classified according to the ICF framework (54-60), such as the Fugl-Meyer Assessment for the upper extremity (FMA-UE) (21), the Action Research Arm Test (ARAT) (25) and the Wolf Motor Function Test (WMFT) (26). The classification for one test may differ between studies as there are no clear boundaries between the ICF components and that a test can include items for more than one component. The WMFT, for instance, involves both items of movement-related functions (Body Functions/Structures) and items of arm functions as carrying, moving and handling objects (Activities) (58). Some authors stress that many existing clinical tests focus on task accomplishment rather than quality of movement (42, 43). Such tests give no or little indication whether improvement after an intervention is due to true motor recovery or to compensation. More recent scales that aim to evaluate quality of upper limb movements are the WMFT (26), the Reaching Performance Scale (61), and the MESUPES (4).

Self-paced gait speed over a short distance (10 m or less) is the most frequently used clinical outcome measure to assess walking ability after stroke (32). To estimate gait kinematics, observational gait analysis is the most common approach in a clinical setting (62, 63). This approach is based on visual (“naked eye”) assessment that may be supported by video recording (62). The majority of observational gait assessments have not been adequately tested for measurement properties (62, 63), and most of them focus only on the lower body (62, 64). One exception may be the Gait Assessment and Intervention Tool (GAIT); a new scale that consists of 31 items of coordinated gait components (65). This scale includes rating of shoulder position, elbow flexion and arm swing. In a recent review by Ferrarello and co-workers, the GAIT was the only observational gait assessment that was recommended for persons post-stroke (63). They further concluded that comparison between observational gait assessments and instrumental gait assessments could be improved such as using summarised 3D data instead of few gait variables such as gait speed and cadence. Examples of indices that summarise 3D gait data are described in the next section.

**Kinematic assessments**

With laboratory techniques it is possible to obtain information of movement patterns and control that cannot be assessed by mere observation in clinical settings. For example, with high-speed motion analysis cameras and force plates, it is possible to achieve kinematic measures (e.g. movement related variables such as position, velocity and acceleration/deceleration, joint angles) and kinetic measures (ground reaction forces). In addition, recording
of muscle activity (electromyography) provide information of the timing and coordination of muscle activation for agonists and antagonists, primary activators and stabilizing musculature.

Optoelectronic motion registration of upper limb movements in persons post-stroke is an objective method to discriminate between motor impairment levels, and to detect changes of motor recovery and possible use of compensatory movements (66). This technique was used in this thesis to analyse upper limb movements after stroke. Optoelectronic motion systems, connected to a computer-processed system for real time analysis, includes cameras using either passively or actively light emitting markers to collect data from the body. The markers are attached on the body, either directly to the skin on specific bony landmarks or in clusters attached on for instance light plastic plates. Prior to the measurement, the system has to be calibrated. A wand is usually moved around in the measurement volume while a stationary reference object in the volume defines the coordinate system for motion capture. When a person moves inside the measurement volume, two-dimensional data of markers that have been recorded by two or more cameras are integrated by the computer and redefined to three-dimensional (3D) data based on this calibration. Three markers per body segment are usually used so that 3D information of respective segments can be appropriately identified (30).

Kinematic analysis of upper limb function is considered most useful for persons with mild to moderate post-stroke symptoms, who have sufficient motor ability to perform voluntary movements (66). Common movements investigated in kinematic studies of persons post-stroke are reaching, pointing, grasping, path drawing and basic ADL tasks (66, 67). Upper limb movements after stroke are usually quantified in terms of temporal (e.g. movement time, speed, and smoothness) and spatial (e.g. joint angles, interjoint coordination and trunk displacement) aspects of movement, which may be obtained by end point and joint kinematics and by calculations of a single marker’s movement (67-69). A recent review concluded that velocity, movement time, smoothness, joint angles and trunk displacement were the most common kinematic measures of upper limb function in persons post-stroke (66). According to the ICF, kinematic measures are classified in the component Body Functions (58, 59).

There are several kinematic characteristics of upper limb movements after stroke described in the literature (68, 70-74). In summary, persons post-stroke demonstrate slower, less smooth, less efficient and less precise upper limb movements compared to non-disabled persons (66). In addition, persons post-stroke may have decreased coordination between shoulder
flexion and elbow extension (71, 73), and may use compensatory movements such as excessive trunk (70) and shoulder movements (68). There are also several studies that have evaluated the effect of different interventions after stroke (49, 75-79). In some studies, using both clinical scales and kinematic assessments to evaluate effects of an intervention, contradictory results have been revealed (78, 79). Kitago and colleagues, for instance, found improvements in the ARAT (Activity) but no improvements in the FMA-UE and kinematic assessments (Body Functions) in persons with chronic stroke after undergoing CIMT (78). They concluded that the functional improvement after CIMT was due to compensatory strategies rather than decreased impairments and return to normal motor control. This finding supports the relevance of combining clinical assessments and kinematic assessments when evaluating upper limb recovery after stroke.

During the last ten years, attention to the upper limb movements during gait in persons post-stroke has increased (29, 51, 52, 80, 81). In contrast to lower limb movements during gait, upper limb movements demonstrate larger variability which is partly explained by the higher degree of freedom in upper limb movements (66). A summary index of upper limb movements during 3D gait analysis after stroke has, however, been lacking. Recently, the Arm Posture Score (APS) was introduced as an index to quantify arm movements during gait in children with cerebral palsy (82). Throughout the gait cycle, the APS summarize an individual’s deviation from a reference group of subjects with no gait pathology, presented as an overall APS score (in the unit degrees). The advantage of a single APS score is that it can be used as a summary indicating severity of deviation of arm swing during 3D gait analysis and further be used in statistical analysis. The APS is based on the same principles as the Gait Profile Score (GPS), which is a summary index of the lower limb movement deviation during gait (83).

**Measurement properties**

All outcome measures should have established psychometric properties, for instance, reliability, validity and responsiveness to change (54). In this thesis, aspects of reliability and validity of some assessments of upper limb function were investigated.

**Reliability**

Reliability can be conceptualized as reproducibility and addresses the degree to which the test is consistent and free from errors. Instrument, inter-rater, intra-rater and intra-subject reliability are common aspects of reliability that are evaluated (84). Instrument reliability is the variation of the assessing test across repeated administrations of the test. Inter-rater reliability is the variation of data between two or more raters who assess the same group of
Introduction

subjects, whereas intra-rater reliability is the variation of data recorded by one rater across two or more trials (2). Intra-subject reliability is associated with variation in subject performance from time to time. Most test-retest reliability calculations involve a combination of instrument errors, examiner errors and true subject variability (84).

Reliability can be quantified and categorized into relative and absolute reliability. Relative reliability examines the relationship between two sets of repeated measurements where the variation is expressed with a correlation coefficient. Absolute reliability indicates the extent to which a score varies between the repeated measurements and is expressed as actual units or as a proportion of the measured values (84). Clinically important changes may be determined by distribution-based methods as the minimal detectable change (MDC) or by anchor-based methods as the minimal detectable important change (MDIC) (85). The MDC describes the property of a measurement based on statistical analysis, whereas the MDIC is usually determined by clinician-based consensus (86).

Validity

Validity reflects the degree to which a test measures what it is supposed to measure (1). Discriminative validity is a form of construct validity that indicates the degree to which the test behaves as hypothesized, for instance, distinguishing pathological movement performance from that of healthy movement performance. Concurrent validity is a form of criterion validity and is studied when the test to be validated is compared with a criterion measure (gold standard) taken at relatively the same time. In other words, concurrent validity is the degree to which the test agrees with other tests that are measuring the same factors (2). There is no well-defined criterion standard when investigating concurrent validity (87). Usually, a well-known clinical scale is used as a gold standard to investigate validity of other existing scales or new scales (26, 88). Kinematic data obtained from optoelectronic motion registration may also be used as a gold standard to investigate concurrent validity of clinical assessments of upper limb function in persons post-stroke (62, 66).
Rationale for the thesis
Research shows that motor recovery after stroke needs to be evaluated in more than one component of the ICF framework and by clinical measures that assess quality of movement (Body Function) during task accomplishment (Activities). There are, however, few existing clinical assessments that incorporate both assessments of task success and quality of movement during the task accomplishment. The Motor Evaluation Scale for Upper Extremity in Stroke patients (MESUPES) is a recently developed measure that evaluates the quality of movement during different upper limb tasks. Although the MESUPES is considered valid and reliable, the absolute reliability and concurrent validity have not been previously investigated.

There is a lack of objective tests to assess arm swing during gait after stroke. The recently developed Arm Posture Score (APS), based on kinematics of arm movements during gait, has not been applied to a stroke population. The APS include movements in frontal and sagittal planes, with no information of rotational movements. As persons post-stroke often have altered rotational movements in the shoulder and forearm, the effect of including rotational components in the APS would be interesting and valuable to evaluate in persons post-stroke.

Optoelectronic motion registration of reflective skin markers provides an objective quantification of motor performance that is more sensitive to investigate subtle upper limb impairments after stroke than clinical tests. This method may be used to investigate underlying construct and measurement properties of existing clinical tests. The Finger-to-Nose test (FNT) and the Nine Hole Peg test (NHPT) are commonly used tests in stroke rehabilitation to assess upper limb function (i.e. coordination and dexterity, respectively). In both tests, time of execution is used as a clinical outcome. The FNT and NHPT have been validated against other clinical assessments but have not yet been investigated concurrently with kinematic analysis.
Aims
The overall aim of the thesis was to evaluate certain measurement properties (i.e. reliability and validity) of existing clinical assessments of upper limb function in persons post-stroke by means of kinematic analysis. A second aim was to further develop existing test procedures and assessments of upper limb function for persons post-stroke.

Specific aims were to:

- establish the inter-rater reliability of the Motor Evaluation Scale for Upper Extremity in Stroke patients (MESUPES), and provide estimates of Minimal Detectable Change for the scale in persons post-stroke (Study I).
- determine the concurrent validity of the MESUPES in relation to the Modified Motor Assessment Scale in persons post-stroke (Study I).
- compare the arm swing during gait in persons post-stroke to that of non-disabled controls using the newly developed Arm Posture Score (APS), a comprehensive index that measures deviant movement patterns in wrist, elbow and shoulder joints (Study II).
- further develop the original APS (including shoulder, elbow and wrist flexion/extension and shoulder abduction/adduction) by adding two movement variables (shoulder internal/external rotation and pronation/supination) to the measure in persons post-stroke (Study II).
- establish the discriminative validity of the Finger-to-Nose test (FNT) in persons post-stroke and non-disabled controls by use of kinematic variables (Study III).
- determine the concurrent validity of the FNT by comparing the total movement time of the FNT performance with kinematic and clinical assessments in persons post-stroke (Study III).
- determine the discriminative validity of the Standardized Nine Hole Peg test (S-NHPT) in persons post-stroke and non-disabled controls by use of kinematic analysis (Study IV).
- investigate the concurrent validity of the S-NHPT by comparing the total movement time of the S-NHPT performance with kinematic and clinical assessments in persons post-stroke (Study IV).
Methods

Materials and methods

The thesis involves four studies. The first study (Paper I) was conducted in a clinical setting at the Neurorehab Sävar, Neurocentrum, Umeå University Hospital, Sweden. The other studies (Papers II-IV) took place at the motion laboratory U-motion lab, Department of Community Medicine and Rehabilitation, Physiotherapy, Umeå University. Table 1 presents an overview of the study designs, samples, and inclusion and exclusion criteria in Paper I-IV. Prior to Study II-IV, discussions regarding current and future assessments of upper limb function after stroke were carried out with two focus groups. The comments from these discussions were taken into consideration when designing the study. In addition, a pilot study of five persons post-stroke was carried out for Study II-IV in order to evaluate the measurement setup and the test protocol and perform power analyses.

Participants

A total of 76 persons post-stroke and 41 non-disabled control persons were assessed in this thesis. A summary of characteristics of participants included in Paper I-IV is presented in Table 2. All stroke participants were recruited from the Umeå University Hospital in Umeå, Sweden. In Study I, 42 adults post-stroke under institutional or outpatient rehabilitation/follow-up were consecutively recruited. In Study II-IV, 34 stroke participants were identified from registers and medical records at the Department of Medicine and Neurorehab Sävar, Umeå University Hospital. Non-disabled controls (n=41) were recruited among staff and acquaintances and through an organization for retired persons.

The sample size for each study was based on power analyses calculated prior to the studies. The different sizes of the stroke samples in Paper II-IV were also due to the stroke participant’s ability to perform the requested tests; walk indoors without aid, touch the nose, and perform a peg test. In study II, the participants in the stroke group were divided into two subgroups regarding spasticity (≥1+ score Modified Ashworth Scale) (89) and gait speed (cut-off 1.0 m/s) (90). And in study III, the stroke group was divided into subgroups based on the FMA-UE; mild (≥50 scores) and moderate-to-severe upper limb impairments (≤49 scores) (91), and by pairing stroke participants with control persons that had close to equivalent movement times. Finally, in Paper IV, the stroke group was divided into subgroups regarding handedness before stroke onset and sensory impairments.
### Table 1. Overview of the four studies in the thesis.

<table>
<thead>
<tr>
<th></th>
<th>Paper I</th>
<th>Paper II</th>
<th>Paper III</th>
<th>Paper IV</th>
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<tbody>
<tr>
<td><strong>Design</strong></td>
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<td></td>
<td>Cross-sectional</td>
<td></td>
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<tr>
<td><strong>Location for data collection</strong></td>
<td>Clinic</td>
<td>Motion analysis laboratory</td>
<td></td>
<td></td>
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<tr>
<td><strong>Study population</strong></td>
<td>Stroke (n=42)</td>
<td>Stroke (n=34) and Controls (n=41)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Subgroups in each paper</strong></td>
<td>Stroke (n=42)</td>
<td>Stroke (n=25) Controls (n=25)</td>
<td>Stroke (n=33) Controls (n=41)</td>
<td>Stroke (n=30) Controls (n=41)</td>
</tr>
<tr>
<td><strong>Inclusion criteria</strong></td>
<td>Unilateral hemiparesis, age 18 years or older, understand verbal and written information</td>
<td>Stroke: &gt;3 months post stroke, unilateral hemiparesis, age 35-85 years, ability to lift hands to mouth, understand verbal and written information</td>
<td>Controls: able to walk indoors without aids Controls: age- and gender-matched</td>
<td>Controls: age 35-85 years</td>
</tr>
<tr>
<td><strong>Exclusion criteria</strong></td>
<td>Other non-stroke related musculoskeletal or neurological problems affecting the upper limb function</td>
<td>Stroke: same as paper I. Controls: musculoskeletal or neurological problems affecting the upper limb function</td>
<td>Stroke: non-stroke related gait problems Controls: problems affecting gait ability</td>
<td></td>
</tr>
<tr>
<td><strong>Measurement properties</strong></td>
<td>Inter-rater reliability and concurrent validity</td>
<td>Discriminative validity</td>
<td>Discriminative and concurrent validity</td>
<td></td>
</tr>
</tbody>
</table>
### Table 2. Characteristics of the participants in all four studies.

<table>
<thead>
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<th>Paper I</th>
<th>Paper II</th>
<th>Paper III</th>
<th>Paper IV</th>
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</thead>
<tbody>
<tr>
<td><strong>Participants, n</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stroke</td>
<td>42</td>
<td>25</td>
<td>33</td>
<td>30*</td>
</tr>
<tr>
<td>Controls</td>
<td>NA</td>
<td>25</td>
<td>41</td>
<td>41</td>
</tr>
<tr>
<td><strong>Male/Female, n</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stroke</td>
<td>27/15</td>
<td>15/10</td>
<td>21/12</td>
<td>19/11</td>
</tr>
<tr>
<td>Controls</td>
<td>NA</td>
<td>15/10</td>
<td>22/19</td>
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<tr>
<td><strong>Age, years [SD]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>BMI, kg/m² [SD]</strong></td>
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<td></td>
<td></td>
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<tr>
<td>Stroke</td>
<td>-</td>
<td>27.1</td>
<td>27.5</td>
<td>27.9</td>
</tr>
<tr>
<td>Controls</td>
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<td>24.5</td>
<td>24.8</td>
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<tr>
<td><strong>Handedness right/left</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Stroke</td>
<td>41/1</td>
<td>24/1</td>
<td>32/1</td>
<td>29/1</td>
</tr>
<tr>
<td>Controls</td>
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<td>24/1</td>
<td>39/2</td>
<td>39/2</td>
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<tr>
<td><strong>Time since stroke, months [SD]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Controls</td>
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<td>11/14</td>
<td>13/20</td>
<td>13/17</td>
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<td>11/14</td>
<td>13/20</td>
<td>13/17</td>
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<td>21/4</td>
<td>28/5</td>
<td>26/4</td>
</tr>
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<td><strong>Motor impairment, scores [SD]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MMAS-UE (max 15)</td>
<td>10.6 [5.5]</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td><strong>Spasticity, yes/no</strong></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>MAS</td>
<td>-</td>
<td>11/14</td>
<td>11/22</td>
<td>9/21</td>
</tr>
<tr>
<td><strong>Grip strength, kg [SD]</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stroke, affected</td>
<td>-</td>
<td>23.6</td>
<td>24.8</td>
<td>26.3</td>
</tr>
<tr>
<td>Controls, non-dominant</td>
<td>-</td>
<td>36.5</td>
<td>35.2</td>
<td>35.2</td>
</tr>
</tbody>
</table>

Abbreviations: BMI, body mass index; MMAS-UE, Modified Assessment Scale for Upper Extremity; FMA-UE, Fugl-Meyer Assessment for Upper Extremity. Spasticity was defined as ≥ 1+ score of Modified Ashworth Scale (MAS) in one or more muscles tested.

*28 persons post-stroke were included in the statistical analysis.
Methods

Ethics
Each participant was presented with written and oral information about the study and signed a written informed consent in accordance with the Helsinki Declaration. The project was approved by the Regional Ethical Review Board in Umeå, Sweden (dnr 070-131M and dnr 2011-199-31M).

Assessments
The assessments used in Paper I-IV are classified into one or more components of the ICF framework and presented in Table 3.

Clinical assessments investigated in the thesis
The Motor Evaluation Scale for Upper Extremity in Stroke patients (MESUPES) was investigated in Paper I. The scale is intended to evaluate quality of movement of the upper limb after stroke. The MESUPES has previously been investigated for internal construct validity and unidimensionality by using Rasch analysis on 398 patients, and also investigated for inter-rater reliability on 56 patients (4). Rasch analysis is a technique which transforms items on an ordinal scale to an interval scale, demonstrating the unidimensional nature of the scale (2). The MESUPES consists of two parts; 1) arm items (n=8) that are performed passively, assisted and actively, and 2) hand items (n=9) that are performed actively. The maximum score of the MESUPES is 58. Prior to Study I, permission to translate the MESUPES was approved by the originators. The Swedish version was translated by using specific guidelines for cross-cultural adaptation (92).

Arm swing during gait. In Paper II, the participants walked several trials at a self-selected speed on a walkway (about 10 m long). The quantification of arm swing that was obtained during the gait test is described in the section of kinematic assessments.

The Finger-to-Nose Test (FNT) is a commonly used test to assess upper limb coordination (93), and is also included in the FMA-UE that evaluates upper limb impairments after stroke (21). In FMA-UE, the time to perform the FNT and the degree of tremor and dysmetria is scored by a 3-point ordinal rating scale. The quantitative measure of the FNT (time of performance) is considered to be more reliable than qualitative assessments of the test (i.e. degree of dysmetria and tremor) (94, 95). In Paper III, the timed FNT was performed as described in the FMA-UE. That is, the person is seated and upon command moves the index fingertip back and forth between the ipsilateral knee and the tip of the nose 5 times, as fast and as accurately as possible.
Methods

The Nine Hole Peg Test (NHPT) is a well-known dexterity test where nine pegs are picked up one-by-one from a box, transferred and inserted into holes of a pegboard until all of the holes are filled, upon which the pegs are then returned one-by-one to the box as quickly as possible (96). The NHPT is considered valid and reliable (59, 97). Recently, the NHPT has been questioned as an outcome measure since the final score is only based on task accomplishment without considering quality of movement (42). For Paper IV, the NHPT was standardised, from now on referred to as S-NHPT, by adding a specific order of which peg to pick and which whole to fill. In addition, the box was replaced with a pegboard. Further details about the construction and standardization of the test are described later in this section and in Paper IV, Figure 1.

Clinical assessments used in different studies

The Modified Motor Assessment Scale for the upper extremity (MMAS-UE) (98) was used as a gold standard to investigate concurrent validity of the MESUPES in Paper I (99). The Motor Assessment Scale is a brief assessment of movement and physical ability after stroke that has good reliability and validity (54). The scale was developed by Carr and colleagues (23) and later modified (98). In contrast to the original version, the modified version includes assessments of both arms and excludes assessment of muscle tone. The maximum score of the MMAS-UE is 15.

The Euroqol 5 dimensions questionnaire (EQ-5D) (100) is a simple, generic measure of health designed as a self-completed questionnaire that can be used in postal surveys, in clinics and in face-to-face interviews. It has been translated into more than 170 languages including Swedish and is available from the website (101), and has adequate reliability, validity and responsiveness (57). The first part contains a descriptive profile of health in five dimensions (mobility, self-care, usual activities, pain/discomfort and anxiety/depression) where each dimension has three or five levels. The second part consists of a visual analogue scale (VAS) on which the respondents rate their state of health from 0 (worst imaginable) to 100 (best imaginable). In Paper I, the first part of the 3-level version of EQ-5 was used as a background characteristic to describe the stroke group (99).

The Fugl-Meyer Assessment for the upper extremity (FMA-UE) (21) is one of the most common assessments of upper limb impairments after stroke, at least in research. The FMA-UE has demonstrated adequate to excellent measurement properties such as reliability, validity and responsiveness (55). The 33-item scale consists of three response categories (scores 0-2) for each item, where a maximum total score of 66 corresponds to unimpaired motor function. The relationship between the FMA-UE and other assessments were
investigated in Paper II-IV. The non-motor subscale of the FMA-UE, sensation (scores 0-12), was assessed as a background characteristic of the stroke group in Paper III and IV, and also used in the statistical analysis in Paper IV.

*The Modified Ashworth Scale (MAS)* grades spasticity in a resting position (89). The 6-point ordinal scale ranges from 0 (no increase in muscle tone) to 4 (affected part rigid in flexion or extension). Muscle tone was tested for shoulder adductors, elbow flexors, wrist flexors, and finger flexors. The MAS has a widespread clinical acceptance, although it reflects only one aspect of spasticity and is best suited to assessing elbow, wrist and knee flexors (55). In Paper II, the relationship between spasticity and arm swing during gait was investigated (102). And in Paper III and IV, the MAS was used as a background characteristic of the stroke group.

*The Stroke Impact Scale (SIS)* is a patient-based, self-report scale that has acceptable psychometric properties according to the originators (103-106). The scale measures impact of stroke in eight dimensions: strength, hand function, mobility, activities of daily living, emotion, memory, communication, and social participation. The first four dimensions create a physical domain. It is translated into many languages including Swedish. The current version 3.0 includes 59 questions with five response categories (scores 1-5), which can be transformed onto a scale from 0 to 100. The last item consists of a VAS on which the respondents rate their perceived recovery from 0 (no recovery) to 100 (full recovery). The SIS (physical dimensions) was used as a background characteristic of the stroke group in Paper IV. In addition, the relationship between the hand function dimension (SIS-hand) and the S-NHPT was statistically analysed.

*Grip strength* was measured with a digital hand dynamometer (Jamar®, US). High test-retest reliability has been reported for the affected arm in persons after stroke (107). In Paper II-IV, grip strength was presented as a background characteristic of the participants, and in Paper IV the relationship between grip strength and the S-NHPT was analysed.
Methods

Kinematic assessments used in the thesis

Data acquisition
Movements during the gait test, the Finger-to-Nose test and the Standardised Nine Hole Peg test were registered using an 8-camera 3-D motion capture system (240 Hz, Oqus®, Qualisys Gothenburg, Sweden). The cameras emitted and captured infrared light reflected by passive spherical markers (diameter of 12 and 19 mm). Single markers were applied with double-sided adhesive tape on defined anatomical landmarks of the body and rigid marker clusters were attached with Velcro straps (Figure 2). The marker setup for the upper body model was slightly different between Study II-IV as described in respective paper. The whole body marker setup for the gait analysis (including lower body model) is described in detail in a parallel paper of Study II (108). Two digital video cameras (Canon Legria HV40), integrated in the motion analysis system, recorded the movements in the sagittal and frontal planes. Kinetic data from two force plates (Kistler, Kirstler Instruments, Winterthur, Switzerland), integrated at the centre of the walkway, were used to identify crucial events of the gait cycles (as described below).

Figure 2. Schematic marker setup for the upper body model in Study II-IV. White markers were those positioned on the dorsal side of the body. Three markers (placed on nose, right and left medial epicondyles) were removed after a static recording for modelling purposes.
**Data processing**

The software Qualisys Track Manager (Qualisys Medical AB, Gothenburg; Sweden, 2.6) was used for capturing, construction of 3D marker coordinates, interpolation of marker trajectories and identification of markers. The data was then exported to the software Visual 3D (C-motion Inc., Germantown, version 5). Data were low pass filtered before further calculations. A 15 Hz critically damped filter was used for the gait analysis while a 6 Hz Butterworth filter was used for the upper limb tasks. Segments used in the kinematic analyses were the head, thorax, upper arms, forearms, and hands. Local segment coordinate systems were defined so that +X represented flexion, +Y represented adduction and +Z represented internal rotation/pronation. The Cardan X-Y-Z sequence was used to extract elbow joint angles and trunk segment angles according to the Joint Coordinate System (109), while the Cardan X-Z-Y sequence was used to calculate shoulder joint angles in Study III (this sequence was selected in order to preserve the anatomical meaning of abduction and flexion at large abduction angles).

A gait cycle was defined as foot-contact to next foot-contact of the same leg. One registered footstep per force plate was used to identify crucial events of the gait cycle. The Finger-to-Nose test was divided into phases; the **Pointing phase** and the **Return phase**, of which the Pointing phase was analysed (Figure 3). The Standardised Nine Hole Peg test was divided into two tasks; 1) the transfer of all pegs from the lateral to the central pegboard (here termed **Transfer task**) and 2) the return of all pegs from the central to the lateral pegboard. In Study IV, only the Transfer task was investigated, and this was in turn divided into two grasping phases; **Peg Grip** and **Peg In Hole**, and two reaching phases; **Peg Transfer**, **Hand Return** (Figure 3).

![Figure 3](image-url)

**Figure 3.** A) The time derivative of the movement of the index finger marker displays the events defining the phases of the Finger-to-Nose test and B) the velocity of the index finger marker in the medial direction displays the events defining the phases of the Standardised Nine Hole Peg test.
Kinematic assessments

The Arm Posture Score (APS) was calculated in accordance to the mathematical construction of the Gait Profile Score (GPS) (83). The root mean square deviation (RMSD) between the patient’s data and the average of the control data was calculated over an entire gait cycle (Figure 4). For each kinematic variable of the upper limb this is referred to as a Gait variable score (GVS\textsubscript{ARM}). For the upper body, the RMSD of four and six GVS\textsubscript{ARM} were calculated, referred to as APS\textsubscript{4} and APS\textsubscript{6}, respectively (Figure 5). The APS\textsubscript{4} includes four GVS\textsubscript{ARM} from the frontal and sagittal planes; shoulder flexion/extension, shoulder abduction/adduction, elbow flexion/extension and wrist flexion/extension (82). The APS\textsubscript{6} includes APS\textsubscript{4} plus two GVS\textsubscript{ARM} from the transversal plane; shoulder internal/external rotation and forearm pronation/supination. A higher APS (in the unit degrees), equates to a higher deviation from normal. The Range of motion (ROM) for each joint movement was defined as the difference between the maximum and minimum values of the angular joint motion curve during the gait cycle (Figure 4). In addition, the GPS and gait speed (m/s) were used as background variables. The GPS is the RMSD of nine gait variable scores based on kinematics from the lower body (83). For all calculations, the data from the right and left arm were analysed separately.

\textbf{Figure 4.} Schematic illustration of the GVS\textsubscript{ARM} and ROM calculation during gait for a person post-stroke with the elbow joint as an example. The shaded area between this person’s curve (bold line) and the curve for non-disabled reference persons (thin line) represents the deviation in movement pattern in the affected side, e.g. GVS\textsubscript{ARM} elbow flexion/extension.
Methods

Figure 5. Graphs illustrating arm movement variables (GVS\textsubscript{ARM}) underlying calculations of APS\textsubscript{4} and APS\textsubscript{6}. Bold line with shaded area represents mean ± 1 SD for a person with post-stroke symptoms and the thin line with shaded area represents mean ± 1 SD for reference data. The x-axis represents 100% gait cycle (GC).

For the FNT and S-NHPT, the selection of kinematic variables used to quantify motor performance was based on proposed valid and reliable variables for pointing and reaching tasks (67, 68, 91, 110, 111). The calculated kinematic variables are described in Table 4. The variables were obtained from an end-point marker attached on the index finger (movement times, Peak speed, Number of Movement Units, Path ratio, Total variability and Variable error), from the kinematic upper body model (Interjoint coordination and Range of motion) or from the acromion-marker (Scapular retraction and Shoulder elevation).
For the FNT, smoothness and efficiency were represented by NMU and Path ratio, while accuracy was represented by Total variability and Variable error. The chosen variables of smoothness, efficiency and accuracy are considered as important characteristics of a well-coordinated movement (1). Interjoint coordination and Time to peak speed expressed as a percentage (TPS%) seemed relevant variables because persons post-stroke usually have altered coordination between shoulder and elbow joints, and thus altered movement strategies in multi-joint reaching (66). Further, speed-related characteristics such as movement times and peak speed were included as the clinical outcome of the FNT is time-based. Finally, spatial variables such as ROM in elbow and shoulder joints, and Scapular retraction were chosen to detect altered or compensatory movements. For the S-NHPT, the selection of kinematic variables was limited to a few variables representing characteristics such as movement times (Total movement time, time of each phase and Grasp-Reach ratio), smoothness (NMU), and compensation (ROM thoracic rotation and Shoulder elevation).

**Test procedures**

**Study I**

*Before the test occasions*
Four raters read the manual of the Motor Evaluation Scale for the Upper extremity in Stoke patients (MESUPES) and had some practical training together (~ 2 hours) and individually.

*During the two test occasions*
Each patient was assessed by two physiotherapists independently within 48 hours. For practical reasons, the physiotherapist responsible for the patient’s rehabilitation completed one of the assessments and a second assessor was randomly selected from the pool of raters. The therapist could ask the participant to repeat the task three times if he or she performed the task inadequately, and the therapist was also allowed to make the participant aware of the abnormal components of the movement. Scoring was performed immediately after the assessment, without any discussion between the raters. The protocols were kept in a locked room until the data collection was finished. The Modified Motor Assessment Scale and EQ 5-D questionnaire were administered after the MESUPES at the first test occasion.
Study II-IV
The data collection in the motion analysis laboratory was part of a larger study that involved five other upper limb tests that were not part of this thesis. Simultaneously with Study II-IV, a parallel study was done to evaluate the effect on the Arm Posture Score (APS) of adding two rotational components and the effect of different gait speed (108). That study addressed methodological aspects of the APS only on the non-disabled controls and was not included in the thesis.

Before the kinematic recording
The questionnaire Stroke Impact Scale (SIS) was posted to participants in advance and returned on the testing day. The SIS answers of the stroke group were followed up when the participants arrived at the motion laboratory. A brief medical history was taken for each participant before beginning the data collection. Weight was obtained using a weight scale (kg) and a stadiometer was used to measure height. The same test leader applied the markers to all participants, who wore tight-fitting shorts and a top.

Kinematic recording of clinical tests
Prior to measurement, the system was calibrated to the measurement volume for the seated tasks and gait analysis, respectively. For the gait analysis, participants walked barefoot at a self-selected speed while looking straight ahead at a cross on the wall placed at eye-level 10 m away from the start position (Figure 6A). There was one practice trial prior to the recorded gait trials. Persons post-stroke walked without walking aids.

For the FNT and the S-NHPT, participants were seated in a height-adjustable chair (Mercado Medic REAL® 9000 PLUS) with their back supported but not restrained. The stroke group performed the test with the non-affected arm first followed by the affected arm, while the control group started with the dominant arm. For the FNT, participants initially held the palm of their hand on the ipsilateral knee, flexed the arm to touch their nose with the tip of the index finger, and returned the hand to the starting position (Figure 6B). With eyes closed, the participants were instructed to repeat five movements as quickly and as accurately as possible. A practice trial of the FNT was performed prior to the single recorded trial. For the S-NHPT, the participants rested their arms on a table in front of them with the test equipment placed on the table (Figure 6C). The participants were instructed to perform the test as quickly and as accurately as possible according to a standardised order. A practice trial of the S-NHPT was performed prior to two recorded trials. The FNT was performed first and the S-NHPT was performed second last of the seven upper limb tests in the sitting position.
Methods

**Figure 6.** The three tasks recorded in the motion analysis laboratory: A) Arm swing during gait, B) the Finger-to-Nose Test, and C) The Standardised Nine Hole Peg Test (S-NHPT). For clarification, the standardised order of which peg to pick and which hole to fill is illustrated with numbers and an arrow indicating the movement direction in the inserted picture of C.
After kinematic recording
Grip strength was measured while seated for all participants. The test position was standardised; shoulder adducted and neutrally rotated, elbow flexed at 95°, forearm and wrist in neutral position (112). The mean of three trials was calculated. For the stroke group, the Modified Ashworth Scale was assessed supine on a bench while the FMA-UE was assessed seated.

Statistical analysis
The Statistical Package for Social Sciences (IBM SPSS Statistics) was used for data analysis. The level of significance was set at p<0.05.

Descriptive statistics
Characteristics of the participants (demographic data, clinical assessments and kinematic assessments) were mainly presented with number, mean and standard deviation (SD) and sometimes range. A few data was presented with median and interquartile range (IQR).

Analysis of differences between two test occasions (Paper I)
The agreement between raters for each item of the MESUPES for the two test occasions was calculated with percentage agreement and linear-weighted kappa (113). The subscores and total scores of the MESUPES were investigated for changes of mean by calculating mean difference and the standard error of the mean difference with 95% confidence interval (86). In addition, the total scores of the MESUPES was tested for heteroscedasticity and outliers. Heteroscedasticity was calculated by Spearman’s rank correlation test. An outlier was considered when the difference between two test occasions was outside 2 SD. For the relative reliability, the Intraclass Correlation Coefficient (ICC) 1.1 was quantified according to a one-way analysis of variance (ANOVA) including 95% CI (2). The ICC1.1 was chosen as persons post-stroke were not all assessed by the same rater. The absolute reliability was calculated by the Standard Error of Measurement (SEM) and the Minimal Detectable Change (MDC) (114). The SEM was calculated by obtaining the square root of the error variance from the ANOVA table. Three levels of MDC were calculated; MDC95 (SEM x 1.96 x √2), MDC90 (SEM x 1.65 x √2), and the MDC80 (SEM x 1.28 x √2). A high ICC along with low SEM and low MDC correspond to a high reliability of the measurement (2). More detailed descriptions of the statistical methods are presented in Paper 1 (99).

Analysis of differences between groups (Paper II-IV)
Normality tests (Shapiro-Wilk test) and variance tests (Levene) were applied before any comparisons were made. Comparisons between groups and
subgroups were conducted with Independent t-test and the Mann Whitney U-test, depending on the data distribution. In Paper III, Glass’s $d$ (115) (parametric) was used to calculate effect sizes of difference between the whole stroke group and the control group. The Glass $d$ was chosen as it is based on SD for the control group (116), which seemed more appropriate than using SD based on combining the stroke group and control group. The $z$-value from Mann-Whitney test was used to calculate effect sizes as $r$ (116) for subgroup analysis in Paper III. The latter was also used to report effect size estimates in Paper IV.

**Analysis of relationships within the stroke group (Papers I-IV)**

Correlation between kinematic and clinical assessments were evaluated using the Spearman rank-order correlation coefficient (Paper I-IV). In Paper II, a repeated measures ANOVA model was used to calculate the influence of hemiparesis and gait speed on APS4 and APS6 (99). In Paper III, univariate and multivariate linear regressions with backward deletion were used to assess how much variance in the time to perform the FNT can be explained by a combination of selected kinematic variables and the FMA-UE. Four independent variables were initially entered in the regression model. Probability for entry in backward regression was set at 0.05 and removal at 0.10. Adjusted $R^2$ value, unstandardized coefficient (B) with their standard errors (SE) and significance value, and unique partial coefficients were reported.
Results

The Motor Evaluation Scale of the Upper Extremity in Stroke patients (MESUPES)

Translation and cross-cultural adaptation
Translation, back-translation, committee review and pre-testing were conducted to ensure quality of the procedure, which is described in detail in Paper I (99). The manual and protocol are available in the Appendix section and at a web page (117).

Inter-rater reliability
Due to the random selection of raters, different pairs of raters assessed 42 patients post-stroke in Study I. Three patients post-stroke were considered as outliers but not excluded in the analysis as nothing had occurred that could explain the differences during or between the two test occasions. There were no systematic biases between the two test occasions of the subscores and the total score since the 95% CI of the mean difference included zero (Table 5). The relative reliability (ICCs=0.98) and the absolute reliability (SEM%<8 and MDC%<22) were high for the subscores and total score. The MDCs for the total score ranged from 5 to 8 points, depending on the confidence level. That means that, at the most stringent level (MDC₉₅), a score change of 8 is necessary to be 95% confident of a real change for an individual patient.

The absolute difference of inter-ratings of total score of the MESUPES ranged from 0 to 13 with a mean absolute difference of 2.0±3.3. There was no significant difference in variation between higher and lower values (two-tailed Spearman p=0.220), indicating no heteroscedasticity in the data.

The agreement between raters for each item of the MESUPES was good to very good according to Percentage of maximum one-score difference (93-100%) and Linear-weighted kappa values (0.63-0.96) (Paper I, Table II) (99). The ratings for the arm items (scores 0-5) were unequally distributed across the arm subscore with less scores at the score level 1 and 2, while the ratings for the hand items (scores 0-2) were distributed across the entire hand subscale.

Concurrent validity
Correlation between the total scores and the subscores of the MESUPES and the MMAS-UE was high (rₛ 0.80-0.87), indicating high concurrent validity.
### Table 5. Reliability analysis of the subscores and total score of the Motor Evaluation Scale for the Upper Extremity in Stroke patients.

<table>
<thead>
<tr>
<th></th>
<th>MESUPES</th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td><strong>Subscore arm</strong> (maximum 40)</td>
<td><strong>Subscore hand</strong> (maximum 18)</td>
<td><strong>Total score</strong> (maximum 58)</td>
<td></td>
</tr>
<tr>
<td>Test 2, mean [SD]</td>
<td>29.3 [14.6]</td>
<td>12.3 [6.2]</td>
<td>41.6 [20.5]</td>
<td></td>
</tr>
<tr>
<td>Mean diff (95% CI)</td>
<td>0.24 (-0.85-1.08)</td>
<td>0.21 (-0.38-0.47)</td>
<td>0.45 (-0.91-1.43)</td>
<td></td>
</tr>
<tr>
<td>ICC_{1.1} (95% CI)</td>
<td>0.98 (0.96-0.99)</td>
<td>0.98 (0.96-0.99)</td>
<td>0.98 (0.97-0.99)</td>
<td></td>
</tr>
<tr>
<td>SEM</td>
<td>2.20</td>
<td>0.94</td>
<td>2.68</td>
<td></td>
</tr>
<tr>
<td>SEM%</td>
<td>7.8</td>
<td>7.7</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>MDC_{80}</td>
<td>3.73</td>
<td>1.6</td>
<td>4.55</td>
<td></td>
</tr>
<tr>
<td>MDC_{90}</td>
<td>5.12</td>
<td>2.19</td>
<td>6.23</td>
<td></td>
</tr>
<tr>
<td>MDC_{95}</td>
<td>6.10</td>
<td>2.61</td>
<td>7.43</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: MESUPES, Motor Evaluation Score of Upper Extremity in Stroke patients; ICC, intraclass correlation coefficients; CI, confidence interval; SEM, standard error of measurement; MDC, minimal detectable change.
The Arm Posture Score (APS)
For the 25 persons post-stroke and 25 control persons in Study II, a minimum of six gait trials per person were achieved except for one person post-stroke who completed four trials. The APS4 and APS6, based on four and six movement variables, were calculated for all participants.

The APS, GVS\textsubscript{ARM} and ROM values for the stroke group and the control group
The APS values were about 5-6° higher in the affected arm compared to the non-dominant arm of the controls (Table 6). In general, significantly higher GVS\textsubscript{ARM} values and smaller ROM values were found in the affected arm compared to the non-dominant arm of the controls, except for the GVS\textsubscript{ARM} pronation/supination and ROM pronation/supination. To investigate whether group differences in APS values were merely related to slower gait speed in the stroke group compared to controls, two subgroups with equivalent gait speed were analysed (unpublished results, right panel in Table 7). Ten selected persons post-stroke with the lowest speed in the whole stroke group in Study II, referred to here as the slow stroke group, were compared with 28 controls taken from our parallel study (108), where they walked at a slow speed set by a metronome. The subanalysis indicated that the APS\textsubscript{4} and APS\textsubscript{6} were significantly higher for the slow stroke group compared to 28 slow walking controls, although both subgroups had the same average speed of 0.66 m/s. Detailed descriptive data of the APS, GVS\textsubscript{ARM} and ROM values for both arms for each group are presented in Paper II, Table 2 and 3 (102). There were no differences between the non-affected arm of the stroke group and the dominant arm of the control group for either APS\textsubscript{4} or APS\textsubscript{6}.

The APS values within the stroke group
For the whole stroke group, the APS values for the affected arm were about 4-5 degrees higher than the non-affected arm (p<0.001, according to the ANOVA with speed as a covariate), as presented in the left panel of Table 7. The subgroup analysis regarding spasticity and gait speed, respectively, in Paper II, Table 2 revealed that the APS values were higher for the 11 spastic persons post-stroke (APS\textsubscript{4} 14.7°±8.5 and APS\textsubscript{6} 15.4°±6.0) than the 14 non-spastic persons post-stroke (APS\textsubscript{4} 9.1°±4.4 and APS\textsubscript{6} 10.6°±3.8), indicating that spasticity had a significant influence on both APS values (102). Further, the APS\textsubscript{4} was significantly higher for the 13 persons post-stroke who walked <1.0 m/s (14.1°±8.0) than the 12 persons post-stroke who walked >1.0 m/s (8.8°±4.5, p<0.05).
Table 6. Arm Postures Scores and Gait Variable Scores (deviation in degrees), and Range of motion (degrees) for the stroke group and the control group. Mean [SD] and p-values are reported.

<table>
<thead>
<tr>
<th></th>
<th>Stroke group (n=25)</th>
<th>Control group (n=25)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Arm Posture Score</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APS₄, four variables</td>
<td>11.6 [7.0]</td>
<td>5.7 [1.7]</td>
<td>0.000</td>
</tr>
<tr>
<td>APS₆, six variables</td>
<td>12.7 [5.4]</td>
<td>7.7 [2.6]</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Gait Variable Score</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GVSₐRM shoulder flex/ext</td>
<td>7.9 [3.6]</td>
<td>4.9 [2.2]</td>
<td>0.001</td>
</tr>
<tr>
<td>GVSₐRM shoulder abd/add</td>
<td>6.6 [4.7]</td>
<td>2.6 [1.1]</td>
<td>0.000</td>
</tr>
<tr>
<td>GVSₐRM shoulder int/ext rot</td>
<td>11.7 [5.0]</td>
<td>8.3 [5.5]</td>
<td>0.015</td>
</tr>
<tr>
<td>GVSₐRM elbow flex/ext</td>
<td>15.8 [13.9]</td>
<td>7.2 [3.2]</td>
<td>0.002</td>
</tr>
<tr>
<td>GVSₐRM forearm pro/sup</td>
<td>13.7 [7.6]</td>
<td>11.2 [5.4]</td>
<td>NS</td>
</tr>
<tr>
<td>GVSₐRM wrist flex/ext</td>
<td>10.1 [5.9]</td>
<td>5.8 [3.0]</td>
<td>0.002</td>
</tr>
<tr>
<td><strong>Range of motion</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM shoulder flex/ext</td>
<td>20.0 [13.3]</td>
<td>28.1 [9.2]</td>
<td>0.010</td>
</tr>
<tr>
<td>ROM shoulder abd/add</td>
<td>8.5 [4.8]</td>
<td>10.8 [2.8]</td>
<td>0.013</td>
</tr>
<tr>
<td>ROM shoulder int/ext rot</td>
<td>15.2 [9.0]</td>
<td>19.3 [7.0]</td>
<td>0.025</td>
</tr>
<tr>
<td>ROM elbow flex/ext</td>
<td>17.6 [13.4]</td>
<td>33.1 [11.2]</td>
<td>0.000</td>
</tr>
<tr>
<td>ROM wrist flex/ext</td>
<td>8.9 [7.0]</td>
<td>15.9 [8.2]</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Abbreviations: APS₄ and APS₆, Arm Posture Scores with 4 and 6 gait variable scores for the arm (GVSₐRM), respectively; ROM, Range of motion; NS, non significant.

**Correlations between the APS values and clinical assessments**

In the stroke group, the APS₄ and APS₆ correlated significantly with the FMA-UE (ₐ =0.73 and ₐ = 0.59, respectively) and with hand strength (ₐ = 0.43 and ₐ = 0.40, respectively).
The Finger-to-Nose Test (FNT)
Thirty-three persons post-stroke were able to accomplish the FNT (Study III).

**Discriminative validity**
All investigated kinematic variables during performance of the FNT, besides ROM in shoulder and elbow joints, were able to discriminate between controls and persons post-stroke (Table 8). Smoothness (NMU), accuracy (Total variability and Variable error), and compensation (Scapular retraction) had the strongest ability to discriminate between controls and persons post-stroke. In the analysis of the two time-matched subgroups (22 stroke, 22 controls), consistent differences were found in NMU, Total variability, Variable error and Scapula retraction. Within the stroke group, Pointing time, Peak Speed, ROM elbow flexion and Number of movement units had the strongest ability to discriminate between mild (n=23) and moderate impairment levels (n=10).

Mean and standard deviation for each kinematic variable regarding the affected upper limbs (stroke group) and the non-dominant upper limbs (control group) are listed in Paper III, Table 2.

**Concurrent validity**
For the stroke group, Total movement time (TMT) was significantly correlated with NMU ($r_s = 0.71$), Time to peak speed % ($r_s = 0.56$), FMA-UE ($r_s = 0.53$), Total variability ($r = 0.47$) and Path ratio ($r_s = 0.38$). The multiple linear regression with backward deletion revealed that the kinematic variables NMU, Time to Peak Speed% and Total variability explained 72% of the variance in TMT. In contrast, the clinical FMA-UE was not associated with TMT in that model.
The Standardised Nine Hole Peg Test (S-NHPT)
All persons except for two persons with stroke (resulting in 28) were able to perform the S-NHPT in the requested order in Study IV.

**Discriminative validity**
Movement times and smoothness (NMU) had the strongest ability to discriminate between controls and persons post-stroke (Table 9).

**Table 9.** Kinematic outcomes of the stroke group and control group performing the Standardised Nine Hole Peg Test (mean and [SD]) and differences between groups (p-values and effect size estimates) are presented.

<table>
<thead>
<tr>
<th>Kinematic variables</th>
<th>Stroke group (n=28)</th>
<th>Control group (n=41)</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total movement time, s</td>
<td>22.42 [8.57]*</td>
<td>12.66 [1.97]</td>
<td>0.72</td>
</tr>
<tr>
<td>Time for <em>Grip Peg</em>, s</td>
<td>0.59 [0.33]*</td>
<td>0.22 [0.09]</td>
<td>0.72</td>
</tr>
<tr>
<td>Time for <em>Peg Transfer</em>, s</td>
<td>0.61 [0.15]*</td>
<td>0.44 [0.07]</td>
<td>0.65</td>
</tr>
<tr>
<td>Time for <em>Peg In Hole</em>, s</td>
<td>0.85 [0.55]*</td>
<td>0.40 [0.12]</td>
<td>0.61</td>
</tr>
<tr>
<td>Time for <em>Hand Return</em>, s</td>
<td>0.57 [0.15]*</td>
<td>0.42 [0.05]</td>
<td>0.58</td>
</tr>
<tr>
<td>NMU for <em>Peg Transfer</em>, n</td>
<td>1.6 [0.5]*</td>
<td>1.1 [0.2]</td>
<td>0.57</td>
</tr>
<tr>
<td>NMU for <em>Hand Return</em>, n</td>
<td>1.5 [0.4]*</td>
<td>1.1 [0.1]</td>
<td>0.44</td>
</tr>
<tr>
<td>ROM thoracic rotation for <em>Peg Transfer</em>, °</td>
<td>3.5 [2.0]*</td>
<td>2.1 [0.5]</td>
<td>0.50</td>
</tr>
<tr>
<td>ROM thoracic rotation for <em>Hand Return</em>, °</td>
<td>3.8 [2.5]*</td>
<td>2.3 [0.5]</td>
<td>0.43</td>
</tr>
<tr>
<td>Shoulder elevation, mm</td>
<td>37.9 [19.3]*</td>
<td>22.2 [9.3]</td>
<td>0.42</td>
</tr>
</tbody>
</table>

*p>0.001; significant group difference according to the Mann-Whitney U test, accompanied with effect sizes r.
The percentage of time spent in every phase was significantly different in persons post-stroke compared to the controls (Figure 7). This gave a Grasp-Reach ratio of $1.22 \pm 0.56$ for the stroke group compared to $0.73 \pm 0.21$ for the control group, indicating that the stroke group spent longer time in the grasping phases (Peg Grip and Peg in Hole) of the task than in the reaching phases (Peg Transfer and Hand Return).

![Figure 7. Percentage of time spent in every movement phase for the stroke group and control group, respectively.](image)

The analysis of the subgroups of right and left handed persons post-stroke revealed no significant relationship between kinematic outcomes and hand dominance before stroke. Persons with sensory impairment in the affected hand used excessive Shoulder elevation compared to those without sensory post-stroke impairments ($p = 0.036$).

**Concurrent validity**

For the stroke group, Total movement time (TMT) was significantly correlated with NMU (Peg Transfer $r_s = 0.58$ and Hand Return $0.77$), FMA-UE ($r_s = 0.60$), Shoulder elevation ($r_s = 0.42$), and ROM thoracic rotation (Peg Transfer $r_s = 0.39$ and Hand Return $r_s = 0.38$). In contrast, the TMT was not correlated with grip strength and SIS-hand.
Discussion

The main findings of this thesis are that the Motor Evaluation Scale for Upper Extremity in Stroke patients (MESUPES) and the Arm Posture Score (APS) provide valid and reliable assessments of limb movements after stroke, in terms of high inter-rater reliability (MESUPES), high discriminative validity (APS) and high concurrent validity (both MESUPES and APS). The MESUPES as well as the APS provide a summary score of specific movement components that can be traced and evaluated separately. Another finding of this thesis is that kinematic analysis, obtained by optoelectronic motion registration, is a useful method to combine with clinical assessments of voluntary movements. The comparison of kinematic data and clinical outcomes (time of performance) of the Finger-to-Nose Test and the Standardised Nine Hole Peg Test, made it possible to investigate the tests’ inherent ability to capture coordination and dexterity, respectively. It was demonstrated that qualitative aspects of the movements, such as compensatory movements in the shoulder, were not sufficiently reflected in the clinical outcomes. Thus, the use of kinematic analysis as a gold standard added new important information about the two tests’ validity.

Motor Evaluation Scale for the Upper Extremity in Stroke patients (MESUPES)

The recommended guidelines, which were used in Study I to translate the MESUPES into Swedish, are primarily designed for questionnaires in which the public or patients answer the questions (92). For a clinical scale, such as the MESUPES, where the clinicians themselves are responsible for assessing and instructing patients, it may seem ambitious to translate a scale in this way. However, as the manual of the original MESUPES contains a lot of text, of which some terms are not fully translatable to Swedish, a more comprehensive translation procedure seemed necessary, although it was time-consuming and resource-demanding.

Several statistical methods were used in Study I to ensure a robust investigation of reliability, including absolute reliability, which is recommended (86). The results indicated a high inter-rater reliability of the MESUPES, even though three outliers were included in the analysis. Regarding minimal detectable change at 95% level of certainty (MDC₉₅), the score change of 8 may seem large for a measurement with a maximum score of 58. However, for the Berg Balance Scale (118), which has a maximum score of 56, the MDC₉₅ has been estimated to a score change of 7 in patients post-stroke (119, 120). From a clinical point of view, lower levels of certainty, as for MDC₉₀ and MDC₈₀, might be enough when interpreting score changes

40
in patients (120-122). For that reason, we provided estimates of MDC of the MESUPES for all three levels of certainty. The study design made it possible to compare results of relative reliability (ICC) and agreement (linear weighted kappa) with the earlier study of MESUPES by Van de Winckel and colleagues (4). The ICC values were high in both studies, indicating high relative reliability. One explanation for the slightly higher ICCs in our study (ICC1,1 = 0.98), compared to their study (ICC2,1 = 0.95-0.97), may be that our sample was more heterogeneous. As ICCs can give misleading results depending on if the sample is heterogeneous or homogeneous, it is recommended that the ICC should not be the only analysis of reliability (86).

The weighted kappa values for the MESUPES-hand test in our study (0.63-0.96) could not be compared with the earlier study since it lacked kappa statistics for the hand items. For the MESUPES-arm test, the kappa-values in our study (0.80-0.92) were somewhat higher than earlier reported (0.62-0.79) (4). The percentage agreement between raters for each item of the MESUPES was high in both studies, although the analyses of percentage agreement were not fully comparable. The sample size (n=42) was less than that of the earlier study (n=56), but was yet considered sufficient (86). Concurrent validity was investigated in Study I by comparing the MESUPES with another clinical test; the Modified Motor Assessment Scale (MMAS). The MMAS was chosen as the scale has been used in previous validity studies (123), and is quick to administer. Even if the correlation between the MESUPES and the upper limb part of the MMAS was high (r_s = 0.87), these results need to be interpreted with caution as this comparison might not be enough to establish sufficient concurrent validity of the MESUPES. Although the average age of the stroke group (56 years) was lower than the national average age for stroke onset (76 years), it did not affect the results since it has previously been demonstrated that age does not contribute to the response of the MESUPES-items (4).

According to the ICF framework, the MESUPES involves items related to neuromusculoskeletal and movement-related functions (Body functions/Structures) and activity-related items such as carrying, moving and handling objects (Activities). The scale has several advantages and could become a useful outcome measure after stroke. Firstly, it only rewards qualitatively correct movements which is a prerequisite for a scale that aims to distinguish motor recovery from motor compensation. Secondly, the MESUPES has a logical order of gradually increasing difficulty beginning with passive, then assisted and then active movements. Thirdly, both subscales have unidimensional characteristics and show no different item functioning across gender, age, country of residence, side of lesion and type of stroke or time since stroke onset (4). Fourthly, the MESUPES does not require a specific location for assessment nor expensive equipment. Despite
many advantages of the MESUPES, there are some considerations about the scale that need to be mentioned. As the MESUPES consists of two subscales with different test procedures and different response categories, the scale requires preparation time when used for the first time. Further, the MESUPES contains a certain degree of subjectivity since the score is based on the assessor’s judgement of quality of movement. Another consideration is that the scale indicates that altered or compensatory movements are present, but not where these abnormal movements occur. Such important information would improve the MESUPES and could preferably be added into the test protocol or described separately.

**The Arm Posture Score (APS)**

Both the APS₄ (including upper limb movements from the sagittal plane and the frontal plane) and the APS₆ (APS₄ plus upper limb movements in the transversal plane) were significantly different between the affected arm and the non-affected arm. Likewise, the APS₄ and the APS₆ were significantly different between the affected arm and the non-dominant arm of the controls, indicating a pathological arm movement pattern. Thus, both APS indices were able to discriminate between impaired and normal arm swing during gait after stroke. The rotational components (shoulder internal/external rotation and pronation/supination) did not increase the discriminative ability of the APS since the variability of shoulder and forearm rotation were high in both arms for each group. Nevertheless, the rotational components provide qualitative information of arm swing that can be useful when evaluating arm swing during gait in persons post-stroke before and after treatments that aim to improve walking ability. For that reason, the APS₆ has an additional benefit over the APS₄. Within the stroke group, spasticity had a significant effect on both APS measures with an increase of approximately 5 degrees. This result indicates that the APS may be useful to detect functional gains in walking in persons post-stroke even though the treatment is applied locally (e.g. botulinum injections in spastic muscles).

The lower speed in the stroke group (0.95 m/s) together with the fact that the APS values were calculated in relation to normal arm swing during self-selected speed (1.30 m/s) in the control group may be debatable. However, this approach represents a common approach in 3D gait analysis as persons with movement disorders usually walk slower than the reference data. The subgroup analysis of 10 persons post-stroke with speed-matched controls (unpublished data), demonstrated higher APS-values in the affected arm compared to the non-dominant arm of the controls. This indicates that other factors than slow speed contribute to higher values of APS measures after stroke. Research findings, indicating support for this hypothesis, have
reported consistent differences in trunk (124) and lower body kinematics (125) during gait in persons post-stroke in spite of equivalent speeds. Further, in a study regarding a gait index for the lower limb variables in persons with rheumatoid arthritis, self-selected speed was able to catch both reduced gait speed and pathology (126), which support the use of self-selected speed for reference values. Within the stroke group, gait speed had a significant effect on the ASP4. Contributing factors to this result might have been the chosen cut-off of 1.0 m/s or other factors that need further exploration.

The APS quantifies deviations in neuromusculoskeletal and movement-related functions and structures (Body Functions/Structures), which is associated with arm swing during gait (Activity). For health care facilities that have access to 3D gait analysis, the APS can be used as an outcome measure after stroke interventions. The APS alone or in combination with the Gait Profile Score (GPS) may help to evaluate deviations in gait in persons post-stroke. This was the case in a recent study of children with unilateral cerebral palsy, where the APS was combined with the GPS to identify different movement patterns (127). Scapular and trunk kinematics are not included in both the APS and GPS calculations, which might be a disadvantage for a gait index as the humeroscapular rhythm is often altered after stroke (128) and that trunk motion influences arm swing (124). On the other hand, it would increase the number of markers and the amount of 3D data to handle. For clinical purposes, the APS6 seems sufficient when describing upper limb movement deviation during 3D gait analysis. Since the APS value gives no indication whether the patient moves the arm more or less than the reference data, all included movement components (GVS\textsubscript{ARM}), together with a qualitative inspection of each kinematic graph and ROM values, are necessary when interpreting the single APS value. ROM for each joint is important to include as the APS and ROM provide different but complementary information (82). It is worth mentioning another summary index of upper limb kinematics; the Arm Profile Score, which describes deviations of 13 upper limb movements during functional tasks in a sitting position (129). The Arm Profile Score is calculated in the same way as the Arm Posture Score and, unfortunately, uses the same abbreviation. Thus, there is a risk that those indices may be mistaken for each other.

**The Finger-to-Nose Test (FNT)**

Previous kinematic studies of pointing and reaching tasks have mainly involved movements away from the body in extra-personal space and less towards the body (66). To our knowledge, this is the first study to investigate the validity of the FNT, as performed in the FMA-UE, against kinematic variables and sensorimotor impairment scales. The use of one-trial outcome
in Study III was in accordance with the test procedure of the Finger-to-Nose
test (21). Although the stroke group performed the FNT slower than the
control group (9.4 ± 3.6 s and 6.8 ±1.9 s, respectively), the variability was
large in the stroke group, and two thirds of the stroke group had similar
movement times to half of the controls. Thus, the discriminative validity of
the total movement time (TMT) of the FNT was sufficient at a group level but
not at an individual level. Despite the fact that persons post-stroke had
mainly mild upper limb impairments, the stroke group demonstrated
differences in 12 of 15 kinematic variables compared to the control group.
Four variables (NMU, Total variability, Variable error and Scapula
retraction) had the strongest ability in discriminating persons post-stroke
from non-disabled controls, and those four variables remained
discriminative even when the movement speed was controlled for.
Smoothness (NMU) was highly correlated with the TMT and associated with
the TMT in the regression model, indicating that the clinical outcome of the
FNT (TMT) mainly reflected temporal coordination. Although the TMT was
correlated with Total variability and the sum score of the FMA-UE, the TMT
did not provide sufficient information about spatial coordination and
possible use of compensatory movements.

According to the ICF framework, the pointing task in the FNT is associated
with control of voluntary movement functions (Body Functions/Structures).
The FNT involves a coordinated pointing movement towards the tip of the
nose which is a small target. By excluding vision while performing the FNT,
the brain has to rely on a body-centred coordinate system (130) where the
source of feedback is intrinsic, i.e. arises from the individual’s own sensory
system (131). This means that sensory mapping is obtained by proprioceptive
information from the joint receptors throughout the movement, and by
tactile information from the fingertip and the tip of the nose when
approaching the final goal. According to Fitt’s law, movement time increases
with distance and accuracy (1). This law may not be fully transferable to the
FNT since the test encompasses a dual task; 1) touch nose tip without vision
and 2) as fast as possible. It might be that this dual task command leads to
different movement times depending on which of these two tasks the person
chooses to prioritize. Thus, a reduction of time to perform the FNT between
two occasions may be a ‘false’ improvement as accuracy may be sacrificed in
favour of increased speed (132). For that reason, it is important to include
qualitative aspects of the performance. The ordinal rating of tremor and
dysmetria, as performed in the FMA-UE, may give some information about
accuracy but is less reliable than the time outcome (94, 95), and does not
consider compensatory movements.
The Standardised Nine Hole Peg Test (S-NHPT)

The NHPT involves carrying, moving and handling pegs (Activity) and control of voluntary movement functions of the upper limb (Body Functions/Structures). Previous studies have classified the NHPT either within Body Functions (59) or Activity (58), showing that the classification of the test according to ICF is not consistent. Although the NHPT has previously been investigated for validity (59, 97), the test has not been compared with kinematic variables. The difficulty of combining the NHPT with kinematic analysis is that it is not possible to quantify the movement trajectories in a reliable and comparable way. Therefore, a standardisation of the NHPT (S-NHPT) was necessary, although this led to results from Study IV not being strictly comparable with previous results of the NHPT. Another result of the standardisation was that the S-NHPT is more cognitively demanding to perform than the NHPT, while the grasp task of the S-NHPT involves a purer pinch grip than the grasp task of the NHPT. Thus, performance of the S-NHPT requires less motor skills than the NHPT, where a peg is picked up from a box and manipulated before it can be placed in a hole. Although an average of three trials of the NHPT has been suggested to be more reliable than one-trial testing (133), this was not done in Study IV. The use of one-trial outcome in the analysis was chosen as this kinematic study aimed to investigate validity of the S-NHPT, which consists of nine reliable repetitions of movements.

The stroke group performed the S-NHPT almost twice as slowly as the control group (TMT 22.4 ± 8.6 s and 12.7 ± 2.0 s, respectively), and the movements were less smooth (increased NMU) than those of the controls. Those findings were not surprising since persons post-stroke have demonstrated prolonged movement times when performing the NHPT (134) and less smooth movements during other upper limb tasks (68, 70, 135). The Grasp-Reach ratio clearly showed that the stroke group spent relatively much longer time in the grasping phases of the task than in the reaching phases, which is another qualitative aspect of the task that cannot be captured by a single outcome measure (total movement time). Further, the stroke group demonstrated increased excessive shoulder motions. This is in line with previous studies which have reported altered scapulohumeral rhythms during shoulder flexion movements (128, 136). Although Shoulder elevation was even more prominent in persons with distal sensory impairments, they had similar movement times as those without distal sensory impairments. This was probably due to compensatory strategies such as vision in order to overcome distal sensory impairments. Regarding concurrent validity, the TMT was correlated with NMU and the FMA-UE but weakly correlated with Shoulder elevation and ROM thoracic rotation,
indicating that the S-NHPT does not sufficiently reflect use of compensatory movements.

Methodological considerations

Study I
The generalizability of the first study is limited to a stroke population in subacute to chronic phases, thus excluding the acute phase. The study design was similar to the earlier study of the MESUPES, which enabled comparisons of some of the results. The translation and cultural adaptation of the scale, and the comprehensive set of statistical analyses to investigate reliability, increased the quality of the study. The concurrent validity of the MESUPES may have been more accurately investigated by using an assessment (gold standard) that more specifically evaluated quality of movement. The study was performed in a clinical setting were the raters were required to perform traditional clinical work alongside the study. Those circumstances sometimes influenced the time window between the two test occasions. In all cases however, test-retest was completed within 48 hours in order to prevent unwanted patient variability.

Study II-IV
The generalizability of the three kinematic studies are limited to a stroke population of predominant mild impairments. The studies were performed in a motion analysis laboratory with new and advanced equipment, and the standardised test procedure was based on previous experience from the laboratory. The test protocol was tested in a pilot study prior to the data collection. The sample size in each study was sufficient for group comparisons according to the power analysis. For the subgroup analysis, however, it would have been preferable to have had larger samples. To minimize errors using 3D motion analysis, the same test leader (GJ) applied all markers on all participants. Each marker location was marked with permanent ink, ensuring that any possible fallen-off markers could be replaced at the same location. The anatomical landmarks were well-defined and usually easy to identify. If there was uncertainty about the correct placement, the marker was checked by another physiotherapist. Even though methodological issues such as soft tissue artefacts are known to affect the outcome measures of the optical motion registration, it has been shown that upper limb motion analysis provides repeatable outcome measures for persons post-stroke (111). The motion analysis system was calibrated for each participant twice (before upper limb tasks in the sitting position and before gait analysis) even if there was more than one participant assessed during the same day. The environment in the laboratory was not like the patient’s usual environment. The minimal clothing as well as the markers
attached on the body may have made it uncomfortable for some of the participants during the recorded assessments. The number of trials for each participant differed between the studies. For Study II, repeated gait trials were needed in order to collect reliable data such as appropriate foot contact on force plates. For Study III and IV, only one trial was analysed, which may seem limited for a kinematic study. However, as the both the Finger-to-Nose test and the Nine Hole Peg test involve several repetitions of movements, data of one trial was analysed in order to investigate validity. The modification of the NHPT by replacing the box with a pegboard led to a version that is not really comparable to the original version and not available on the market. Nevertheless, it is possible to repeat the study by using two commercial versions of the NHPT and place the pegboards in the same way as described in Study IV. Consequently, all three kinematic studies are reproducible.

Clinical implications and future research

Motor recovery after stroke
During the last decade, the length of stay in Swedish hospitals has decreased due to effective stroke units and early supported discharge. Consequently, the rehabilitation as well as the assessments of upper limb recovery are mainly conducted in the patient’s home at earlier stages after stroke. Modern stroke rehabilitation focuses on increasing the patient’s functional recovery and autonomy by using task-oriented approaches and other evidence-based treatments. Nevertheless, there is an ongoing debate worldwide regarding what stroke rehabilitation should focus on; improvement of functional recovery in patients regardless of how the task is performed or improvement of functional recovery through reappearance of premorbid movement patterns and task performance as in a healthy condition (1, 42, 43). From my point of view, compensation should be avoided if there is potential for motor improvement and that compensation prevents or masks normal movement patterns. For patients with mild-to-moderate upper limb impairments, there are good possibilities to improve functional recovery by reducing motor impairments, improving quality of movement and promoting normal task performances. But, for severely impaired patients, compensatory strategies may be the only alternative to increase their ability to perform activities and to be involved in real-life situations. In all cases however, it is important that clinicians assess several aspects of functional recovery such as motor functions, quality of movements, task success and quality of task accomplishment. To increase knowledge about true motor recovery and compensation, and how to best treat persons post-stroke, more RCT studies are needed, especially in the earlier phases of stroke.
Clinical assessments of upper limb function after stroke

It is proposed that stroke-specific outcome measures should be classified into the ICF framework in order to clarify which component that is measured and to distinguish between motor recovery and compensation (43, 44). As the majority of existing outcome measures were developed before the turn of the century, when focus was on motor impairments and disability, most stroke-specific outcome measures are classified within Body Functions and Activity. In 2001, when the ICIDH was replaced with the ICF, new components such as Participation and Contextual factors were introduced (31). Still, there are few outcome measures that assess voluntary upper limb use with regard to actual performance (Activity) and involvement in real-life situations (Participation). The classification of assessments is not consistent in the literature since there are no clear boundaries between the ICF components and that a test often include items in more than one component. Despite this lack of clarity within the ICF framework, it is important to incorporate the terminology of ICF in stroke rehabilitation and in national guidelines of stroke care.

There are many clinical tests to choose between when assessing movement deficits in persons post-stroke or evaluating effects of stroke-specific interventions. It has been suggested that there should be a consensus of a smaller number of robust, standardised, and relevant outcome measures to enable comparisons between studies (11, 44). From a research perspective, it sounds sensible to make such agreements. One way to provide such consensus of outcome measures is to collate existing evidence from multiple reviews. However, such evidence is not constant and would thus need to be regularly updated due to newer measures which may prove to be better or supplement existing well-established tests. From a clinical perspective, it is not necessary to limit clinicians to a small number of outcome measures since few tests are applicable to the whole range of the stroke group. The stroke population is a heterogeneous group who are assessed and treated in different stages of recovery and in different environments. Therefore, it is useful to have several outcome measures to choose between as long as those measures have sound measurement properties.

In this thesis, one ordinal rating scale and two time-monitored tests of upper limb function in persons post-stroke were investigated. The clinical implications that can be drawn from the results are as follows. Motor Evaluation Scale for Upper Extremity in Stroke patients (MESUPES) is a new scale that can be easily performed at home and preferably be used as a supplement to functional tasks in order to distinguish between motor recovery and motor compensation. The scale’s equipment consists of some common items that are portable and inexpensive. Although the MESUPES is
considered valid and reliable, further investigation of validity and other measurement properties such as responsiveness is encouraged.

The timed Finger-to-Nose test (FNT) can be used as a quick measure of temporal coordination after stroke. That is, the longer time to perform the FNT for a person with stroke, the less smooth are the movements and the longer is the deceleration phase of the pointing movement. When using the timed FNT, one should be aware that persons post-stroke may have similar movement times to those of non-disabled individuals, at least in persons with mild upper limb impairments. Therefore, qualitative aspects of coordination such as dysmetria, tremor and possible compensatory shoulder motions should be included when the FNT is used to assess upper limb coordination. Upper limb coordination is complex and needs to be studied further in order to develop methods that can examine this phenomenon in a valid and reliable manner.

The Nine Hole Peg test (NHPT), is a time-monitored test, which can be used to assess dexterity function in persons post-stroke. The clinical outcome (time of task accomplishment) of the NHPT indicates that the longer time of performance in a person post-stroke, the less smooth are the movements and the more severe are the upper limb impairments. However, one should be aware that the timed NHPT does not provide sufficient information about task performance. Therefore, complementary measures of how the task is performed are needed when interpreting a time reduction (improvement) of the NHPT. To achieve more reliable comparisons between test occasions or between groups, a standardization of the current NHPT is required. The standardised NHPT, as described in this thesis, is not available on the market today and its clinical utility needs to be studied further.

**Kinematic assessment of upper limb function after stroke**

Kinematic analysis of the upper limb after stroke, by using optoelectronic systems, is most useful for examination of active movements in persons with mild-to-moderate impairments (66). This method is not commonly available in clinical practice since it is based on resource-demanding technology where the produced complex data has to be interpreted and understood (63). In Sweden, there are few motion analysis laboratories that are used for clinical purposes and the current ones focus mainly on 3D gait analysis. To increase the clinical use of 3D gait analysis, complex gait data are presented in convenient reports and summarised indices (e.g. Gait Profile Score). A similar simplified management of 3D analysis of the upper body and upper limbs is desirable.
In this thesis, the Arm Posture Score (APS) was applied to persons post-stroke. The results indicate that the APS is a useful index when quantifying deviation of arm swing during gait after stroke. The single APS score may be used as an overall summary of severity of arm swing deviation, whereas the underlying subscores may be used to evaluate deviations of specific movement components for the shoulder, elbow and wrist joints. The utility of the APS in persons post-stroke seems promising but needs to be studied further. It would be interesting to investigate how successful the APS is when measuring deviations over time, to evaluate impact of interventions, and to classify patients into clinically relevant groups. Further, the APS, together with the Gait Profile Score, could be used as gold standards in order to develop valid tools of observational gait analysis. From a clinical point of view, more attention should be paid to arm swing during gait in persons post-stroke since it has been demonstrated that increased arm swing amplitude and normalized interlimb coordination reduce energetic cost and facilitate movements of the legs during walking (50). Such effects may in turn reduce overall fatigue after stroke and perhaps more independent and safer locomotion in general for this group. Since the therapeutic value of arm swinging is not well-studied, more research of gait rehabilitation after stroke is needed.

Computerised 3D motion analysis provides an objective quantification of upper limb movements that increases the understanding about recovery of stroke among researchers, clinicians and patients. It would be preferable if more health care facilities in Sweden were to have access to a kinematic motion analysis laboratory, at least when it comes to larger hospitals. Such laboratories could, for instance, provide clinicians and researchers with objective assessments of upper limb function in persons post-stroke, based on high-quality and reliable equipment. Portable motion sensor systems may also be used to assess the upper limb after stroke (137-139), not least in evaluating real-life activities at home or outdoors. Video recordings and observational motion analysis could also give important information if motion analysis laboratories are inaccessible. According to the ICF, assessments of functioning in a standardised environment (e.g. motion analysis laboratory) describes Capacity, whereas assessments of functioning in the patient’s real environment (e.g. portable motion systems) rather describes Performance. Whatever system is used, physiotherapists have an important role in interdisciplinary teams when interpreting motion data and transferring results into clinical relevance that can benefit the patient. Therefore, it is important that physiotherapists try to integrate this technology into clinical practice and keep themselves updated on its development and associated research.
Conclusions

This thesis showed that existing clinical assessments of upper limb function in persons post-stroke are valid and reliable even though some limitations were found, for instance the Finger-to Nose test had insufficient discriminative validity. Kinematic analysis provided unique information about the validity of the tests in Study II-IV and gave additional outcome measures (in the form of kinematic variables) that may be used in further development of clinical assessments. The most important conclusions are listed below:

Reliability and validity of the MESUPES:

- The Motor Evaluation Scale for Upper Extremity in Stroke patients (MESUPES) has high inter-rater reliability. The Minimal Detectable Change for the total score of the MESUPES ranges between 5 to 8 points, depending on the level of statistical certainty (Study I).
- The concurrent validity of the MESUPES was high, but further research is needed to confirm this (Study I).

Usefulness of the Arm Posture Score to assess deviating arm motion:

- Both the original and the modified Arm Posture Score (APS₄ and APS₆, respectively) discriminate between impaired and normal arm swing during gait after stroke (Study II).
- In order to conclude whether APS₆ is more informative than APS₄, the two additional variables in APS₆ (shoulder internal/external rotation and pronation/supination) need to be studied further. Since the indices describe merely whether or not a motion pattern deviates but not how, the range of motion and a qualitative inspection of the kinematic graphs should be taken into account when interpreting the APS score. The rotational variables (shoulder internal/external rotation and pronation/supination) did not increase the discriminative ability of the APS. Nevertheless, the rotational variables provide qualitative information that could be useful when evaluating walking ability in patients with post-stroke symptoms or patients with other movement disorders (Study II).
Validity of the Finger-to-Nose test and the Nine Hole Peg test:

- The time to perform the Finger-to-Nose test (FNT) has insufficient discriminative validity at an individual level, at least for persons with mild post-stroke impairments. Movement smoothness, accuracy and compensation, which were provided using kinematics, were the most discriminative variables (study III).
- The time to perform the FNT may be used as a measure of temporal coordination but not as an overall measure of coordination. The time to perform the FNT is most correlated with temporal kinematic variables and with upper limb impairments, and the variance in the timed FNT is best explained by movement smoothness (Study III).
- The time to perform the Standardised Nine Hole Peg test (S-NHPT) has high discriminative validity. Also, smoothness and compensatory shoulder elevation are able to discriminate the S-NHPT performance in persons post-stroke from that of non-disabled controls (Study IV).
- The timed S-NHPT is most strongly related to smoothness and upper limb impairments, indicating that compensatory movements such as shoulder elevation are not sufficiently taken into consideration (Study IV).
- Kinematic measures based on phase analysis showed that the stroke group spent a significantly longer time grasping and releasing pegs relative to the reaching phases of the task compared to controls. This emphasised the decreased dexterity among the post-stroke persons (Study IV).
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Appendix
Dissertations written by physiotherapists, Umeå University 1989–2015

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