The Assessment of Capacity for Myoelectric Control
To my parents
HELEN LINDNER

The Assessment of Capacity for Myoelectric Control

Psychometric evidence and comparison with upper limb prosthetic outcome measures
Abstract


Evaluation of outcomes using validated prosthetic outcome measures (OMs) is a current priority in upper limb (UL) prosthetics, and OMs with psychometric evidence toward UL prosthesis users are thus necessary. The “Assessment of Capacity for Myoelectric Control” (ACMC) is a tool that assesses the ability to control a myoelectric prosthetic hand. Some psychometric aspects of the ACMC have been previously investigated, but others are still lacking. A major part of this thesis was thus to search and assess the psychometric evidence of the ACMC. Data were collected from prosthesis users of different ages, prosthetic sides, and sexes. Rasch analysis was used to search for validity evidence and activity influence on the users’ ACMC ability measures, while reliability statistics was used to search for reliability evidence. Overall, the validity evidence was satisfactory in terms of unidimensionality, item technical quality, item difficulty, and relation to prosthetic wearing time. In terms of activity influence, the majority of prosthesis users received similar ability measures in different activities. Reliability evidence was also satisfactory in terms of test-retest reliability and rater agreements (intra- and interrater).

Besides the ACMC, several other prosthetic OMs have been developed in recent years. A comparison of these OMs would help professionals to select appropriate tools for clinical practice. Thus, a comparison of the validated UL prosthetic OMs was performed with an emphasis on what health aspects they cover. Eight OMs were chosen, and their contents were linked to the “International Classification of Functioning, Disability and Health” (ICF). The results showed that the contents from different OMs were linked to the ICF categories in “Body functions,” “Activity and Participation,” and “Environmental Factors.”

In conclusion, the use of a mixture of OMs is recommended to cover different aspects of health. Based on the evidence in this thesis, the ACMC can be recommended to measure the ability to control a myoelectric hand.

Keywords: Capacity, Comparison, ICF, Myoelectric Control, Psychometric evidence, Upper limb prosthesis.

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List of publications underlying this thesis


**List of abbreviations**

<table>
<thead>
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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AA</td>
<td>Acquired amputation of upper limb</td>
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<tr>
<td>ACMC</td>
<td>Assessment of Capacity for Myoelectric Control</td>
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<tr>
<td>CAA</td>
<td>Center for Arm Amputees</td>
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<tr>
<td>CAPP-FSI</td>
<td>Child Amputee Prosthetics Project - Functional Status Inventory</td>
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<td>CAPP-PSI</td>
<td>Child Amputee Prosthetics Project - Prosthetics Satisfaction Inventory</td>
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<tr>
<td>CTT</td>
<td>Classical test theory</td>
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<tr>
<td>DIF</td>
<td>Differential item functioning</td>
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<tr>
<td>ICC</td>
<td>Intraclass coefficient</td>
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<tr>
<td>ICF</td>
<td>International Classification of Functioning, Disability and Health</td>
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<tr>
<td>κ</td>
<td>Kappa</td>
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<tr>
<td>LDAPC</td>
<td>Limb Deficiency and Arm Prosthesis Centre</td>
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<tr>
<td>LOA</td>
<td>Limits of agreement</td>
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<tr>
<td>MDC</td>
<td>Minimal detectable change</td>
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<tr>
<td>MDC$_{95}$</td>
<td>Minimal detectable change at 95% confidence level</td>
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<tr>
<td>MCID</td>
<td>Minimal Clinical Important Difference</td>
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<td>MFRM</td>
<td>Many-Facets Rasch model</td>
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<td>MnSq</td>
<td>Mean Square</td>
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<td>OMs</td>
<td>Outcome Measures</td>
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<td>OPUS</td>
<td>Orthotics and Prosthetics Users’ Survey</td>
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<td>OT</td>
<td>Occupational therapist</td>
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<tr>
<td>PA</td>
<td>Percentage agreement</td>
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<tr>
<td>PCA</td>
<td>Principal components analysis</td>
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<td>P &amp; O</td>
<td>Prosthetics and Orthotics</td>
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<td>PUFI</td>
<td>Prosthetic Upper Functional Index</td>
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<tr>
<td>RSM</td>
<td>Rating Scale Model</td>
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<tr>
<td>SE</td>
<td>Standard error</td>
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<td>SEM</td>
<td>Standard error of measurement</td>
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<tr>
<td>SIRS</td>
<td>Skilled Index Rank Scale</td>
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<tr>
<td>SSC</td>
<td>State-of-the-Science Conference</td>
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<tr>
<td>TAPES</td>
<td>Trinity Amputation and Prosthesis Experiences Scales</td>
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<tr>
<td>UBET</td>
<td>Unilateral Below Elbow Test</td>
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<tr>
<td>UL</td>
<td>Upper limb</td>
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<td>ULRD</td>
<td>Upper limb reduction deficiency</td>
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<td>UNB</td>
<td>University of New Brunswick Test</td>
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<td>Zstd</td>
<td>Z-standardized</td>
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Preface

When I started working at the prosthetic clinic, I met an old friend who had not been fitted with prostheses when we first met. During a tea break in the clinic’s kitchen, this friend now used the prostheses to make drinks and sandwiches. I asked if this friend would get together with other friends in town, to which this individual responded, ‘…now I can go out with friends because I have my prostheses…I use them to pick up my coffee mug and sandwiches…I can eat comfortably now in public.’ This friend even said, ‘I want to show you what I can do now compared with the first time you met me’ (shared with permission).

This conservation always stays in my mind. It encourages me because it tells me that prosthetic fitting can give a normal life back to a person. It motivates me when I plan prosthetic training for my clients, with a focus on helping them to gain success in controlling their prostheses step by step. During my clinical practice, I have found that instruments that assess how my clients control their prostheses are helpful because the assessment results can help me to plan my training. At our clinic, we use an assessment method, the Assessment of Capacity for Myoelectric Control (ACMC), to evaluate how our clients control their prostheses. From time to time, however, my colleagues and I would discuss questions concerning the assessment results, namely the ACMC ability measures. We discussed questions such as, ‘Will the clients obtain different ability measures when they perform different activities?’, ‘How consistent is the ACMC ability measure?’, and ‘How do we know that there is a change in the ability of a patient when we compare the current and previous ability measures?’ All of these questions are relevant for us as clinicians when we interpret the ACMC ability measures. Previous psychometric validations of the ACMC were satisfactory, but further validations are needed to answer the above questions. Therefore, my primary goal in embarking on this thesis has been to answer the above questions.

Furthermore, apart from the ACMC, are they any other prosthetic outcome measures that we can use to assess our patients, such as prosthesis use in daily life? What are the similarities and differences among different prosthetic outcome measures? How do we select an appropriate measure for the aim of a given evaluation? In response to these questions, a minor but important part of this thesis involved comparison of upper limb (UL) prosthetic outcome measures to identify their similarities and differences. My hope is that this part of the thesis will help us as clinicians to select appropriate measures for the aims of our evaluations.
1 Introduction

Individuals with upper limb reduction deficiency (ULRD) or acquired amputation of upper limb (AA) are often fitted with UL prostheses to compensate for limb absence.\(^1\) The goal of prosthetic fitting is to provide users with the means to function optimally within their social and physical environment.\(^2\) If a myoelectric prosthesis is chosen, the user will learn to control the prosthesis with voluntary muscle contraction. Training is usually offered to help users achieve an adequate level of control so that they are able to use the prostheses effectively in their daily lives.\(^3\) To monitor their progress in controlling their prostheses, it is necessary to assess in a standardized manner how UL prosthesis users control their prostheses. In response to this demand, the Assessment of Capacity for Myoelectric Control (ACMC) has been developed.\(^4\)

1.1 The Assessment of Capacity for Myoelectric Control

The ACMC is an observational assessment developed to assess the ability of a prosthesis user to control a myoelectric prosthetic hand.\(^4\) Each item in the assessment is an observable prosthetic hand movement or an observable prosthetic hand movement in relation to other body parts (see Results - ‘From version 1.0 to version 2.0’ for the item lists). The assessment session is often carried out during the user’s performance of a bimanual activity. It is designed for upper limb (UL) prosthesis users of different ages, prosthetic levels and sides.

The ACMC assesses capacity for myoelectric control. Let’s take a look at the following definitions:

<table>
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<th>Definitions</th>
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<td><strong>Capacity</strong> - an individual’s mental or physical ability.(^5) It also refers to what a person <em>can</em> do in a standardized environment.(^6)</td>
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<tr>
<td><strong>Myoelectric</strong> - ‘myo’ means muscle in Greek and ‘myoelectric’ refers to electrical activity produced by a contracted muscle.(^7)</td>
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<tr>
<td><strong>Control</strong> - the skill in the use of a tool.(^5)</td>
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Merriam-Webster defines ‘capacity’ as mental or physical ability of an individual.\(^5\) Indeed, for many UL myoelectric prosthesis users, it takes a lot of mental and physical effort to achieve an adequate level of capacity for myoelectric control.\(^8\) The *International classification of functioning, disability and health* (ICF) describes ‘capacity’ as an individual ability to execute a task or
an action.9 ‘Capacity’ is what an individual with a health condition can do in a standardized environment6 and the ICF suggests that using standardized environment for assessments allows international comparisons of individuals.9 ‘Capacity’ can be measured with or without assistive device9 and both ways of measuring capacity has been used in prosthetics.10, 11 In the ACMC, an individual’s capacity for myoelectric control is assessed when an individual is wearing his/her UL prosthesis and the assessment is often taking place in a standardized environment, such as prosthetic clinic.

Myoelectric signal is the signal generated during muscle contraction.7 In the ACMC context, a skillful myoelectric prosthesis user is one that is capable to control the prosthesis with appropriate muscle contraction. The capacity for myoelectric control does not come instantly when an individual puts on a prosthesis, rather, it may take a lot of mental and physical effort, especially during the first months after prosthetic fitting.8, 12 The challenges in controlling a myoelectric prosthesis can be described in terms of a number of aspects related to the capacity for myoelectric control. However, to understand these aspects, it is important to have a basic understanding of the individuals who use UL prostheses and the control of a myoelectric prosthetic hand. Therefore, these topics are presented in the next few sections.

1.2 Individuals who use upper limb prosthesis

Individuals with congenital upper limb reduction deficiency

Congenital limb deficiency is suggested to occur between the 3rd and 8th week of embryogenesis.13 It is relatively rare, with an estimated worldwide rate of 2 to 7 per 10,000 live births14 (upper and lower limbs) and 3.7 per 10,000 in Sweden (UL).15 An estimated 12% to 33% of limb deficiencies are associated with other major congenital anomalies or genetic disorders,14 while the remaining limb deficiencies occur as isolated limb defects. Children with isolated limb defects of the UL often develop normally, and they can perform most age-appropriate activities, although the activities may be performed in an atypical manner such as with the help of chin, mouth, or elbow.16, 17 Patients with unilateral below-elbow deficiency constitute the largest group that benefits most from myoelectric prosthetic fitting.18 They often have a healthy, intact UL on the nondeficient side and a functional shoulder and elbow on the deficient side.19

Prosthetic rehabilitation for children with ULRD emphasizes the development of the child.20 The prosthetic socket is changed regularly to accommodate residual limb growth, and the prosthetic hand size is chosen to match the
intact hand size. The activities used for training are age-appropriate.\textsuperscript{3} Prosthetic fitting at an early age is recommended because it encourages motor learning and prosthesis integration into the body scheme.\textsuperscript{21} It has been suggested that prosthetic fitting promotes overall symmetry of development.\textsuperscript{22, 23} The type of prosthesis prescribed to the child is dependent on the child’s cognitive ability, attempt to hold objects manually, and attention span for training.\textsuperscript{24} In Sweden, children are usually fitted with cosmetic prostheses before they have achieved sitting balance and are fitted with myoelectric prostheses between 2.5 and 4 years of age.\textsuperscript{25} Researchers have explored phantom sensation in persons with ULRD,\textsuperscript{26, 27} but whether these individuals have an innate dominant side remains unknown. From clinical experience, those with right-sided ULRD are often more spontaneous in using their prostheses than are those with left-sided ULRD.

**Individuals with acquired upper limb amputation**

Amputation refers to the surgical or spontaneous partial or complete removal of a limb or projecting body part covered by skin.\textsuperscript{28} Work-related injuries and traffic accidents are the two major causes of amputation.\textsuperscript{14, 29} In the last decade, an increasing number of amputees have lost their limbs as a result of war.\textsuperscript{30} Therefore, it is difficult to precisely determine the incidence rate of AA, but in general, Scandinavia has a lower incidence rate than do other countries.\textsuperscript{14} In Sweden, one study estimated a hand/forearm amputation incidence rate of 3.3 males/0.5 females per 100,000 persons.\textsuperscript{31} Another Swedish study estimated a rate of 5.21 per 100,000 persons for all types of amputations; 62\% of them occurred at working age, and 16\% of amputees were less than 20 years old.\textsuperscript{32}

Individuals with unilateral below-elbow amputation constitute the largest amputated group fitted with UL prostheses.\textsuperscript{33-35} Amputation surgery is performed to preserve the length and muscle balance of the residual limb for prosthetic fitting.\textsuperscript{35} Prosthetic fitting should start as soon there is no open wound because early fitting may be positively related to prosthetic acceptance.\textsuperscript{17} Pain management is offered because many amputees experience different types of pain, such as phantom limb pain.\textsuperscript{36, 37} It was recently found that strong phantom limb pain is associated with decreased prosthesis use.\textsuperscript{38}

In brief, prosthetic fitting for both groups (ULRD and AA) is a highly individual process. The patients are informed about different prosthetic options, such as cosmetic, body-powered, hybrid, and myoelectric-controlled prostheses,\textsuperscript{39} because different prostheses have different strengths and limitations. Myoelectric control is the most commonly used control in commercial pros-
thetic hands. Although the media occasionally report ‘bionic’ hands that are controlled directly by the human mind, most currently used myoelectric prostheses are controlled by voluntary muscle contractions that require a lot of practice and training.

### 1.3 A myoelectric prosthetic hand – how to control it?

Myoelectric prosthetic hands are controlled with voluntary muscle contraction. Myoelectric signals generated during muscle contractions are detected by surface electrodes embedded in the prosthetic socket (Fig. 1, left). The signals are then amplified and sent to the appropriate prosthetic component to generate the desired movement.

Surface electrodes are often placed over antagonistic muscles of a residual limb or muscles that can be voluntarily contracted in an isolated manner. The best muscle sites for surface electrodes are selected during socket fabrication (Fig. 1 right). A well-fitted socket, optimal muscle sites, good myoelectric signals, and good skin contact with surface electrodes are essential for the user to control a myoelectric prosthesis.

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Fig. 1. **left** – two surface electrodes embedded inside a prosthetic socket; **right** – myoelectric signal examination (this image - courtesy from Advanced Arm Dynamics)

Fig. 2. **left** – a below-elbow prosthesis; **middle** – an Otto Bock VariPlus Speed Hand for adults; **right** – an Otto Bock 2000 myoelectric prosthetic hand for children (courtesy from Otto Bock)
In a typical below-elbow (transradial) prosthesis with two surface electrodes (Fig. 1 left, Fig. 2 left), the hand opens when the surface electrode over forearm extensors picks up myoelectric signals that exceed the electrode threshold. Conversely, the hand closes when the surface electrode over forearm flexors picks up myoelectric signals that exceed the threshold. Different control formats are offered in prosthetic hands, and one of them is an on/off format in which the hand speed is constant during both opening and closing. The on/off format is a common format for children’s prosthetic hands. Adult myoelectric hands offer several control formats. One common format is ‘proportional control,’ in which the hand speed and closing force are proportional to the amount of muscle contraction given by the user.

Although commercial multifunctional hands with articulating fingers have been available since 2007, the majority of myoelectric prosthesis users are fitted with a prosthetic hand in which the motor drives the index and middle fingers synchronously with the thumb. The last two fingers are not articulated, but serve as support during grasping (Fig. 2 right). The thumb lines up with the tips of the two fingers (Fig. 2 middle), and the hand can thus perform two grips: a cylindrical grip and a tripod pinch (Fig. 3 left, middle). Prosthetic hands come in different sizes and with different opening widths and grip forces that match the user’s growth.

Controlling a myoelectric prosthesis is different from controlling a human UL. One obvious reason is that the arm muscles were originally developed for physiological functions other than controlling a myoelectric prosthesis. The first challenge for novice users is to isolate muscle contraction. Users must learn to contract one muscle site while relaxing the other muscles of the residual limb. When the users try too hard, they co-contract the muscles used for opening and closing; hence, the hand will neither open nor close. The users may produce unwanted muscle contraction, which causes unintended movement. For example, the user may accidentally activate the ‘opening’
muscle and open the prosthetic hand when holding a cup (Fig. 3, left), which may cause the user to drop the cup. Alternatively, the user may produce too much muscle contraction during closing, such as grasping a toothpaste tube (Fig. 3 right), unintentionally squeezing out the toothpaste. When holding objects, the user must relax the arm muscles so that myoelectric signals are maintained below the electrode thresholds.

1.4 Aspects related to capacity for myoelectric control

Compared with the number of studies on prosthetic components, literature on learning to control a myoelectric prosthetic hand is sparse. Some publications have an occupational therapy perspective, focusing on training from basic control to use training. A few articles have evaluated the effects of training. A kinesiology team used motor learning to describe prosthetic movement. In addition, a movement science team recently used motor learning to understand skill acquisition in prosthesis users. Different challenges related to capacity for myoelectric control can be found from these studies, and they can be summarized according to six different aspects.

(1) The need of external support

Prosthesis users often have difficulty opening and closing the hand in space because of the weight of the prosthesis. The sudden increase in weight at the residual limb induces unintended muscle activity that interferes with the intended muscle activity, and the hand thus opens or closes involuntarily. Unintended muscle activity often disappears immediately when the user loads the prosthetic weight on a table or solid support. Novice prosthesis users must overcome this challenge because many activities require the users to perform reaching movements in space. One way to overcome this is to acclimate the residual limb to the prosthetic weight by wearing the prosthesis on a daily basis. The interference from unintended muscle activity will gradually diminish.

(2) Grip force and opening width

Another challenge for prosthesis users is accurate application of an appropriate prosthetic grip force during grasping. Novice users often produce too much contraction, and the object either slips out of the hand or is crushed by the hand. They must learn to regulate the grip force with an appropriate amount of contraction (in proportional control) or with an appropriate duration of closing (in on/off control). Another challenge for prosthesis users is the difficulty adjusting the opening width when releasing objects. Many users find it challenging to perceive the magnitude of hand opening.
(3) Coordination of both hands
It takes some practice for prosthesis users to coordinate the movements of the prosthetic hand and intact hand. The speed of a myoelectric prosthetic hand is determined by two features: (i) the time window during which the myoelectric signals must exceed the electrode threshold, and (ii) the hand speed designed by the manufacturer. The speed of a prosthetic hand is obviously slower than that of a human hand; however, a user who is familiar with the speed of his/her own prosthetic hand can skillfully coordinate the hands, as demonstrated by the ability to remove the cap from a pen. The user begins to contract the ‘closing’ muscle early enough so that both hands can grasp objects in a coordinated manner.

(4) Different positions and in motion (timing)
Another challenge is the use of a prosthetic hand in different positions. This may be difficult because when the arm is in different positions, unintended muscle activity may be produced, resulting in involuntary opening or closing. Another challenge is use of the hand with good timing when the hand or arm is in motion. This ability can be observed when the user is passing objects between the hands or passing an object directly with the prosthetic hand to another person. The object may get stuck in the prosthetic hand if the user does not release the object quickly enough. In a similar way, it takes some practice to hold objects securely when the arm is in motion (Fig.4 left) because unintended muscle activity may activate the opening electrode and cause the object to be dropped.

![Fig.4. Left – Holding object when the arm is in motion; middle, right – not looking at the prosthetic hand when holding objects (courtesy from Otto Bock)](image)

(5) Repetitive grasp and release
Switching quickly between opening and closing is a challenging movement. This is an advanced skill of myoelectric control because the user must contract the pair of muscles in a swift manner. Repetitive grasping and releasing is useful for object manipulation, such as altering the object position. Prosthe-
sis users who are not capable of repetitively grasping and releasing objects often change the object positions with compensatory movements such as shoulder abduction and trunk deviation. It has been suggested that long-term performance of compensatory movements may cause shoulder pain. Researchers have suggested that some compensatory movements can be avoided with certain prosthetic movements, such as repetitive grasping and releasing.

(6) The need of visual feedback
Sensory feedback is an essential component for accurate dexterous actions. A myoelectric prosthesis does not provide direct sensory feedback; therefore, the user cannot feel whether the hand is opened or closed or whether the object is being held securely. Many users find it challenging to perceive the magnitude of hand opening/closing or the strength of the grip force exerted on an object without direct feedback. They often look at the hand during the operation, and great concentration is needed. However, very experienced users reportedly do not look at the prosthetic hand during grasping. Some users have claimed that they hear the hum of the motor or feel the motor vibration during muscle contraction. Sörbye reported a young blindfolded patient who grasped an object with her prosthesis without acoustic feedback. Experienced users may be able to perceive vibration changes during the grasping and holding of objects, thus not requiring visual feedback (Fig. 4 middle, right). The need for less visual feedback is an advanced level of myoelectric control that enables the user to use the device efficiently.

In summary, the above six aspects are challenges that prosthesis users will experience while learning to control their prostheses. One study reported that younger children learn more quickly than older children do, and another study on adults suggested that different users may have different learning capacities. To evaluate the client’s progress in controlling the prosthetic hand, a reliable and valid instrument that evaluates the ability to control a myoelectric prosthetic hand is thus needed.

1.5 Prosthetic training – an occupational therapy perspective
From an occupational therapy perspective, the ultimate goal of prosthetic training is to help the user to integrate the prosthesis into his/her daily life and achieve independence. Prosthetic training often starts with control training. The first step of control training is to help the user to discover how to open and close a prosthetic hand. For example, when the user extends the forearm to reach for an object, the hand grip opens because the extensors activate the ‘opening’ electrode. The training focuses on grasping and releasing objects of varying sizes, shapes, textures, and weights.
When a prosthesis user has achieved basic control of his/her prosthesis, the training can shift to use training. Use training focuses on refinement and use of the prosthesis.3 Purposeful activities, such as playing with toys and everyday activities, are always used as tools in use training.42, 51, 52 The use of activities during training not only enhances immediate performance, but promotes the learning of a prosthetic skill.54, 79 For example, during meal preparation, the user practices grasping different delicate food products with ‘appropriate grip force’ or practices using the prosthesis ‘in different positions’ when grasping bowls and plates from different shelves. During use training, the prosthetic hand is often used to stabilize objects while using the intact hand to manipulate objects during the activity.52 The occupational therapist (OT) also regularly identifies the user’s goals. For example, children may be preparing for school activities, whereas adults may aim to achieve self-dressing. Once the goals are identified, the OT provides training for the activities. Furthermore, to help the users build habits of integrating the prosthesis into their daily lives,24 they are encouraged to wear their prostheses on a daily basis.51

Smurr53 uses the term ‘advanced prosthetic training’ to describe a more advanced level of training. The idea is to teach the user the most efficient approach to complete an activity using the prosthesis without causing too much stress or awkward body movements. The training goal is to help the user to incorporate the prosthesis efficiently and demonstrate a natural motor pattern. The length of prosthetic training depends on different factors, such as the complexity of the prosthetic components, learning capacity of the user, motivation, and family support.3, 53, 65

1.6 A tool is needed to assess capacity for myoelectric control

Prosthetic training can be frustrating at times, especially during the first few months of training. The muscles may not contract as the user intends. The hand may open when the arm is moving. Failure to control the prosthesis may lead the patient to eventually stop using the prosthesis. It is therefore very important for the OT to monitor the user’s progress in controlling the prosthesis because it helps the OT to adjust the training pace and direction and, most important, to help the prosthesis users achieve success with the right level and amount of training step by step. One way to monitor the user’s progress is to use an assessment tool that is able to capture different aspects related to the capacity for myoelectric control, because the assessment result can identify in which aspect the users need more training. Although monitoring the user’s progress is important, prosthetic clinics reportedly do not use any standardized assessment tests, but rely on their own tests in follow-up evaluations.24 One problem with clinic-owned tests is that the efficacy of
training cannot be compared among prosthetic services. Some clinics use human hand function tests to evaluate prosthetic function, but it has been suggested that hand function tests may not provide valid results because they do not address prosthetic-related issues and many compensatory movements may occur during the tests. Although a variety of outcome measures have been used to measure outcomes among UL prosthesis users, none of those developed before the ACMC were designed to assess different aspects related to capacity for myoelectric control. In response to this demand, the ACMC was developed in 2000 and its first validation was published in 2004.

1.7 The development of ACMC

The beginning of ACMC
Just more than two decades ago, the Skills Index Ranking Scale (SIRS), a stepwise description of movement quality in myoelectric control, was developed. This scale contains a series of steps that describe different ability levels in myoelectric control. However, one problem associated with the SIRS is that the differences in ability steps are unknown; thus, it cannot be used as an evaluation tool. However, the steps in the SIRS were selected to be the items in the ACMC. After two pilot trials and expert selection, extra items were added to ACMC, resulting in the ACMC version 1.0.

ACMC version 1.0
The ACMC version 1.0 comprises 30 items that assess 6 aspects related to the capacity for myoelectric control. (see also Results - ‘From version 1.0 to version 2.0’ for item list).

- The need for external support - 8 items
- Grip force and opening width - 3 items
- Coordination of both hands - 2 items
- In different positions and in motion (timing) - 8 items
- Repetitive grip and release - 2 items
- The need for visual feedback - 7 items

Each item has a definition that guides the raters in identification of the movements. Items that assess ‘the need for external support’ are easily performed by users who can position their hands in space. Items that assess visual feedback are generally difficult for prosthesis users. The ACMC items are therefore not only different in terms of movement, but also in terms of difficulty.
A 4-point rating scale (version 1.0) is used to rate the items. Category ‘0 - not capable’ is assigned when the user cannot or does not perform the item. Category ‘1 - sometimes capable’ is assigned when physical or verbal guidance from the OT is needed. Category ‘2 - capable on request’ is assigned if the user only performs the item when the rater asks the user to perform it. Category ‘3 - spontaneous and skillful control’ is given when the user performs the item spontaneously and skillfully. Because the activities are user-chosen during ACMC assessments, it is possible that one or two ACMC items are not required in the activities. For example, the item ‘holding without crushing’ will not be performed if no delicate object is involved in the activity. The item will then be rated as ‘missing.’

An ACMC assessment
An ACMC assessment is administered by raters who have taken the training course. It can be carried out as soon as the user can open and close the prosthetic hand. The prosthesis user is encouraged to choose an activity, and the ACMC rater assesses how the user controls his/her prosthetic hand during activity performance. For example, if the client chooses to set a table for afternoon tea, the activity steps are screw off a bottle cap, take things from the fridge, or place a tablecloth onto the table etc.

During performance of the activity steps, the rater observes the six above-described aspects, such as how capable the user repetitively grasps and releases objects (Fig. 5, left), how well the user controls the prosthetic hand in different positions (Fig. 5, middle), and the timing of releasing objects (Fig. 5, right). The rater scores the items and enters the ratings into the ACMC website, where the built-in Rasch model software calibrates an ACMC ability measure for the user (see ‘ACMC – a Rasch-built measure’ for Rasch analysis). Each ACMC assessment evaluates only one prosthetic hand; therefore, a bilateral user with two myoelectric hands can have two ACMC assessments (based on one activity performance) and obtain two ability measures.
Activities for ACMC assessment

An ACMC assessment is often carried out during the client’s performance of a self-chosen activity. This means that the activity is selected according to the development and interest of the user. During the assessment, the user is encouraged to perform the activity in his/her usual way. The prosthetic hand is usually used to hold objects, while the intact hand is used to manipulate objects (Fig. 6 left). For unilateral users, the prosthetic hand is always used as the nonpreferred or nondominant hand, regardless of the side of dominance before amputation. Therefore, an ACMC assessment is performed to determine how the prosthetic hand is being used as an assistive device.

Although the activity is chosen by prosthesis users, ACMC raters must consider two practical issues regarding activity objects. First, the activity objects must cause the hand to open. This means that the objects must be small enough to loosely fit inside the grip of the prosthetic hand. Adult prosthetic hands have large opening widths, but pediatric prosthetic hands have small opening widths (e.g. 33mm to 56mm for Otto Bock children 2000) and, the thumbs do not have an adduction function. Objects that are too large for the prosthetic hand will lead to passive prosthesis use (Fig. 6 middle). Since the ACMC assesses active prosthesis use, activities involving small objects or small handles are appropriate for ACMC assessment (Fig. 6 right). Furthermore, small children can tolerate very little loading in their hands, and the objects must therefore be light. Second, the objects must be placed at different heights and in different locations to stimulate the user to stretch out the prosthetic side in different positions. Accordingly, the activity must be able to stimulate the user to change prosthetic hand functions and UL movement so that the user’s ability to control his/her prosthesis can be assessed.
1.7.1 ACMC – a Rasch-built measure

The first validation of ACMC version 1.0 was carried out using Rasch analysis. Rasch analysis is an alternative to Classical Test Theory (CTT) for psychometric development of an instrument. With CTT, rank-ordered data are often summed to give a total score but it cannot be assumed that rank-ordered categories define equal intervals along the underlying construct. In Rasch analysis, rank-ordered categorical data are converted into interval logit measures and a change from 1 to 2 logits is the same as the change from 2 to 3 logits. One useful function of Rasch analysis is that it orders items in terms of difficulty along an equal-interval unidimensional underlying construct. The sample of patients are also located along the same underlying construct which allows the developer to investigate whether the instrument has items to measure low, moderate and high levels of the underlying construct. This is important for the ACMC because the ACMC is expected to encompass the wide range of abilities encountered in clinical practice. Another useful function of Rasch analysis is the analysis of rating scale. A rating scale with rating categories that are confusing for its users, such as too wide or too narrow, would lead to inaccurate ratings. There is a family of Rasch models, such as ‘Rating Scale Model’ (RSM) and ‘Many-Facets Rasch Model’ (MFRM), available for different types of analyses.

Although there are different Rasch models, the basic principle of Rasch model is that a person’s response to an item depends on the difference between the person’s ability and the item’s difficulty on a hypothetical underlying construct. Instead of using summed raw scores to represent a person’s ability directly, Rasch analysis converts raw scores into odds (which for dichotomous data is the probability of success on an item over the probability of failure on the item, and for rating scale data, odds are also used but the algebraic expression is more complex). The natural logarithm of the odds converted from a person’s raw score gives a linear measure in logits (log-odds unit) that represents the person’s ability. An item’s difficulty is also estimated from its odds but now on the probability of failure over the probability of success.

Both items and persons have the same logit units and therefore they can be placed side by side along a common logit scale (often displayed as a vertical scale), which visualizes the ability range of a group of persons and the difficulty range of a set of items (Fig. 7). In Fig. 7, the items are located along the logit scale according to their difficulty (commonly known as item difficulty hierarchy) and the persons are located along the logit scale according to their ability. Ideally, the item difficulty range and the person ability range should
target well on each other (so-called targeting) and their mean logits should be close to each other because this suggests that the set of items are appropriate to measure the ability of the sample.

Fig. 7. An illustrative example to show item difficulty hierarchy and targeting (each represents one person in a sample and each item represents one item in an instrument)

The Rasch model constructs unidimensional linear measures from the data. The fit of the data to the model can be evaluated by comparing the observations in the data with their Rasch expectations:

For person measure, a more able person must always have a better chance of success on an item than a less abled person. For item measure, any person must have a better chance of success on an easy item than on a more difficult item.

The Rasch model provides fit statistics for items and persons to determine how well the data fit this expectation. If the item fit statistics are within an acceptable range, then the items contribute to a unidimensional construct or have good technical qualities. Depending on the type of outcome measures, different acceptable ranges for fit statistics have been suggested; for example, a wider range is suggested for clinical observational data than for survey data.

In the first validation of ACMC version 1.0, item fit statistics were used to indicate unidimensionality, and fit statistics for all items met the model expectation of unidimensionality. Person fit statistics (96.2% of the sample) were also within the acceptable range, and the items targeted well at the ability of the sample. Instrument validation is an ongoing process, and the thesis continued this process in terms of evaluating the validity and reliability evidence of the ACMC.
1.7.2 Validity aspects of the ACMC

In 1999, the Standards endorsed Messick’s view on validity and redefined validity as the degree to which evidence and theory support the interpretation of test scores entailed by proposed uses of tests. Messick emphasizes that validity is not a property of a test, but is the meaning of test scores for its proposed use. Instead of different types of validity, validity is viewed as a unitary concept that is established by accumulating evidence from different sources. The Standards outlines five sources of evidence to guide developers in the conduction of validation studies: test content, response processes, internal structure, relations to other variables, and the consequence of a test. The process of instrument validation therefore entails accumulation of evidence to provide a sound empirical foundation for the proposed interpretation of test scores. This thesis continues this validation process of ACMC by conducting studies to search for evidence from the following sources:

Evidence based on content evidence
According to Messick, content evidence includes content relevance, content representativeness, and technical quality. Different approaches have been suggested to collect content evidence, such as expert judgment on contents or the conduction of small pilot trials. In the beginning of the ACMC development, expert judgment and two pilot trials were used to select suitable items. The Rasch approach has been suggested to address content representativeness by using item strata (statistically distinct regions of item difficulty that the persons have distinguished). The first ACMC validation shows that the prosthesis users separated ACMC items into 16 item strata, which is considered as excellent. Further content evidence is the technical quality of an item, for which Messick refers to technical quality as ‘unambiguous phrasing’ of items/questions. Rasch item fit statistics has been suggested to examine the technical quality of items because the misfit of an item (fit statistics outside the acceptable range) reflects the extent to which a significant portion of the sample responds inconsistently to that item. Item fit statistics can also identify redundant items that do not contribute much information to the test score. An item with fit statistics that is above the acceptable range should be investigated with further analyses because the item may contribute data that threaten the validity of the test score.

Evidence based on response processes
This source of evidence refers to the fit between the construct and the detailed nature of performance or responses actually engaged in by individuals. According to Messick, this evidence answers the question, ‘How well do the response processes demonstrate the construct?’ Rasch approach has been
suggested to address this source of evidence using rating scale analysis, item difficulty hierarchy and person fit statistics. Person fit statistics was demonstrated earlier in the first validation of ACMC.4

- A rating scale with rating categories that are confusing for its users, such as too wide or too narrow, would lead to inaccurate ratings. The analysis of rating scale functioning enable us to examine how the rating scale categories function in relation to the underlying construct. For example, a rating scale category with a narrow definition would occupy a narrow range along the construct.

- The item difficulty hierarchy orders items from easiest to most difficult along the hierarchy. The responses to the items are used to estimate item difficulty; therefore, the ordering of item difficulty provides important evidence on how the ability of prosthesis users demonstrates the construct. Furthermore, the targeting of this hierarchy on the abilities of prosthesis users also provides evidence for this response process.

Evidence based on internal structure
This source of evidence concerns the degree to which the relationships among test items conform to the construct on which the proposed test score interpretations are based. Validation examples are unidimensionality and differential item functioning (DIF).4, 105, 106, 113

- Unidimensionality concerns whether all items measure one or more than one attribute. If the items measure more than one attribute, then it is difficult for clinicians to distinguish which attribute the test score is presenting. Unidimensionality was previously demonstrated in the ACMC using item fit statistics.4 However, as suggested by later methodological studies, item fit statistics should be supplement with other methods such as ‘principal components analysis’ (PCA) to investigate unidimensionality.

- DIF occurs in an item when two groups of persons with same ability have different chances to perform the item successfully for reasons unrelated to the construct being measured. The existence of DIF may suggest a flaw in the internal structure. If DIF exists in one or several items, the next question would be, ‘To what extent does the DIF affect the item location along the item difficulty hierarchy?’ In reality, it is not unusual for items with similar difficulty measures to swap locations along the item difficulty hierarchy. However, further analyses or actions must be taken if the DIF makes an easy item become difficult (or vice versa) for a certain person characteristic.
Evidence based on relations to other variables
This evidence concerns the relationship of test scores to variables external to the test.\textsuperscript{105} Validation examples are the correlation with other known variables/instruments and known-group comparisons from widely used variables in the field.\textsuperscript{106, 117} The variable ‘prosthetic wearing time’ is a widely used variable that indicates prosthetic acceptance or daily prosthesis use.\textsuperscript{19, 45, 88, 118-121} Wearing the prosthesis on a daily basis helps the user to adjust to the prosthetic weight and provides the opportunity to use the prosthesis in different daily activities. Therefore, there is a possibility that ACMC ability measures would be higher in full-time users than non-full-time users. Another external variable is hand dominance. Hand dominance has been used as a variable that indicates prosthesis use,\textsuperscript{118, 119, 122} and dominant-sided users have been shown to have higher abilities than non-dominant-sided users.\textsuperscript{123}

Construct-irrelevant variance
While searching for evidence, Messick states that it is important to examine threats to test score validity.\textsuperscript{104} One threat is construct-irrelevant variance, which refers to the degree to which the scores are affected by processes that are extraneous to its intended construct.\textsuperscript{105} Construct-irrelevant variance is always present to some extent,\textsuperscript{124} and the question is how much the extent affects the test scores. In the ACMC, construct-irrelevant variance could arise from client-chosen activities. Although the purpose of using activities in ACMC assessment is to stimulate the users to change hand functions so their ability can be assessed, it is unknown how much the activities affect user ability measures. One way to investigate this is to ask prosthesis users to perform different activities on one occasion and examine whether different activities give different ability measures. Furthermore, it is necessary to examine whether different activities favor a particular sex or prosthetic side.

1.7.3 Reliability aspects of the ACMC
Reliability refers to the consistency of such measurement when a testing procedure is repeated on a population of individuals or groups.\textsuperscript{105} Inconsistent assessment scores are difficult to interpret and therefore reduce validity evidence.\textsuperscript{125} Similar to validity, reliability is not viewed as a property of a test, but an interaction among the instrument, sample, and situation.\textsuperscript{126}

Reliability of the ACMC ability measures can be influenced by various sources. First, variations among prosthesis users can play a role in the reliability of ACMC ability measures. Because great mental and physical effort may be required to control a myoelectric prosthesis, the ACMC ability measure may fluctuate randomly if the person is stressed or tired. Second, the trans-
duction of myoelectric signals can be affected by factors such as sweat and pressure on the electrodes. Third, the ACMC raters may introduce variations into the ability measures. Rater reliability for ACMC version 1.0 was investigated among three raters with different ACMC experiences, and more experienced ACMC raters produced more consistent ACMC scores than did less experienced raters. New evidence of rater reliability has to be searched if an instrument has a new version.

One important aspect of reliability that has not been previously evaluated in the ACMC is the stability of ACMC ability measures over time. If ACMC measures are not stable over time, then it is difficult to use the ACMC to detect changes in ability among prosthesis users or to conclude that a specific change is the result of an intervention. The amount of error from repeated measurements can be used to calculate the ‘minimum detectable change’ (MDC), which suggests the smallest change that can be detected by the instrument beyond measurement error. The MDC is a useful clinical value for the ACMC because it can serve as a guideline to show whether a change between ACMC assessments over time is due to measurement error or is a real change.

To summarize, there are several aspects of evidence available to ascertain the quality of an assessment tool. In the ACMC, some of these aspects have been investigated, but others have not. The demand for outcome measures with psychometric evidence is increasing in the field because pressure from insurance companies and prosthesis users has prompted prosthetic professionals to demonstrate the benefits of prosthetic fitting. According to the American Academy of Orthotists & Prosthetists State-of-the-Science Conference (SSC) in 2009, measuring outcomes with validated prosthetic outcome measures is a current priority in the UL prosthetic field. It is therefore necessary to continuously search and assess the psychometric evidence for using the ACMC to evaluate the ability to control a myoelectric hand.

1.8 Measuring outcomes with validated prosthetic outcome measures

Functional outcomes in UL prosthesis users can be measured from different perspectives. If the aim of evaluation is the client’s ability to control his/her myoelectric prosthesis, then the ACMC may be an appropriate tool. If the client’s opinion about the device or daily prosthesis use is the aim of evaluation, then a client-rated questionnaire that measures UL prosthetic-related issues would be an appropriate tool. After the development of the ACMC in 2004, several UL prosthetic outcome measures were validated. Similar to the ACMC, these outcome measures were not designed for a study-specific pur-
pose, but their developers had one common goal: to produce a reliable and valid outcome measure with which to measure the functional outcome in prosthesis users. One common aspect of these measures is that they have been validated with UL prosthesis users in contrast to other instruments using subjects with normal hands for validation, which has been a common practice in UL prosthetic research.\textsuperscript{135} Assessment of prosthesis users to validate UL prosthetic outcome measures is necessary because the items/questions are intended to measure UL prosthetic-related issues and the findings are likely to be more valid than those using subjects with normal hands.

These validated UL prosthetic outcome measures are important to our field because they have the potential to provide reliable and valid measurements that reflect our patients’ statuses. However, it is not easy for clinicians to know what these outcome measures are actually measuring because most of them are primarily focused on measuring ‘function,’ and the concept of ‘function’ can have different meanings for different professionals. An OT considers ‘function’ to be the person’s ability, but a UL prosthetic engineer refers to ‘function’ as the technical performance of a device. One way to understand the similarities and differences of outcome measures is to compare them by linking the content of the measures to the ICF.\textsuperscript{136}

1.8.1 Content comparison using the ICF

The ICF is a framework developed by the World Health Organization to describe human functioning.\textsuperscript{136} This classification goes beyond diagnosis to increase our awareness of the consequence of a disease. Impairments in body function and/or structure, such as loss of a part of or the whole UL, may lead to activity limitations or limited participation.\textsuperscript{137} The attitude toward disability has therefore shifted from a purely medical focus to a bio-psycho-social focus.

The three ICF components ‘Body functions and structures,’ ‘Activities and participation,’ and ‘Environmental factors’ are classified into different categories. A prosthetic hand is an ‘environmental factor,’ but it also partly replaces the ‘body functions and structures’ of a human hand. The ICF has been used in a study to measure functioning among users of prosthetics and orthotics (P & O) at a P & O outpatient clinic; their functioning increased when they were using P & O devices.\textsuperscript{10} The ICF categories have also been used to explore functioning in acquired amputees.\textsuperscript{138} These two studies suggest that the ICF is useful to describe functioning of UL prosthesis users.
One useful aspect of the ICF is that it serves as a common language for different professionals to describe health-related status. This is particularly useful for our field, which comprises professionals from different disciplines. Because the validated UL prosthetic outcome measures were developed by practitioners from different disciplines, they may use the same terminology, but with different meanings. Therefore, a content comparison of these UL prosthetic outcome measures may provide a clear picture of their similarities and differences. The ICF has been proven to be useful for content comparison of similar measures in other fields. \(^{139-141}\) Researchers have commented that such comparison may help with the selection of an appropriate outcome measure and may identify the aspects of health that are lacking in the measures.

To summarize, the newly validated UL prosthetic outcome measures have the potential to produce reliable and valid measurements that help us to make clinical decisions and demonstrate the benefits of prosthetic fitting. A content comparison of these outcome measures may therefore help professionals choose appropriate outcome measures for their clinical practice.

### 1.9 Rationale of the thesis

Good control of UL myoelectric prostheses may ease users’ performance in their daily activities\(^ {57, 88}\) but it may take a considerate amount of training and practice to achieve an adequate level of control. To monitor users’ progress in controlling their prostheses, a clinical tool that assesses how prosthesis users control their prostheses would be clinically useful. An assessment tool that can capture different aspects related to the capacity for myoelectric control can help the OT adjust the training pace and direction and, most importantly, help the prosthesis user achieve success in a step-by-step manner with the right level and amount of training. Although a variety of outcome measures have been used to measure outcomes among UL prosthesis users,\(^ {83}\) none of them, before the ACMC, are designed to assess the capacity for myoelectric control. In response to this demand, the ACMC was developed, and two psychometric validations showed that this tool has the potential to produce reliable and valid measurements. However, several important evidence related to the validity and reliability of ACMC are still lacking, such as the technical quality of ACMC items (content evidence), empirical item difficulty hierarchy (response processes evidence), DIF (internal structure), relations to external variables such as prosthetic wearing time and hand dominance, stability of the ACMC ability measures over time, and the influence of activity on the ACMC ability measures. Instrument validation is a continual process, and this thesis continued this process by searching and assessing the evidence re-
garding use of the ACMC to measure the ability to control a myoelectric prosthetic hand.

Measurement of the interaction between the UL prosthesis user and his/her prosthesis is challenging, and one outcome measure alone cannot fully grasp the whole picture of this interaction. The ACMC can only capture one part of this interaction; other outcome measures are needed to capture the other parts of this picture. Several UL prosthetic outcome measures have been developed in the last decade, including the ACMC. However, it is not always easy for clinicians to know what these new measures are actually measuring because quite a few of them are primarily focused on ‘function’ or ‘functional status,’ but their items/questions are different. Therefore, a content comparison of these outcome measures using the ICF may facilitate the selection of appropriate outcome measures in clinical practice.
2 Aim

The aim of the thesis is to search and assess the psychometric evidence regarding use of the ACMC to measure the ability to control a myoelectric prosthetic hand and to compare the contents of UL prosthetic outcome measures using the ICF.

Specific aims:
- To evaluate the construct and rating scale of the ACMC (Study I)
- To evaluate the influence of standardized activities on the validity of ACMC (Study II)
- To evaluate test-retest reliability and rater agreements of ACMC version 2.0 (Study III)
- To perform a content comparison of UL prosthetic outcome measures using the ICF (Study IV)
3 Materials and Methods

3.1 Study Design

For Studies I-III, a cross-sectional study design was chosen, and for Study IV, a systematic review was applied. Two ACMC versions have been used in this thesis; ACMC version 1.0 was used in Study I, and the results led to the development of version 2.0. Version 2.0 was then used in Studies II, III, and IV (see Results - ‘From version 1.0 to version 2.0’).

3.2 Participants in studies I, II and III

The participants comprised individuals with either ULRD or AA of different ages, sexes, and prosthetic sides (Table 1). They were recruited from two clinics in Sweden: the ‘Limb Deficiency and Arm Prosthesis Centre’ (LDAPC) at Örebro University Hospital and the ‘Center for Arm Amputees’ (CAA) at Red Cross Hospital in Stockholm.

Table 1: Participant demographics in Studies I-III

<table>
<thead>
<tr>
<th>STUDY</th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>Sep 00–Dec 04</td>
<td>Sep 09–Apr 11</td>
<td>Sep 09–Jun12</td>
</tr>
<tr>
<td>Clinic</td>
<td>LDAPC</td>
<td>LDAPC</td>
<td>LDAPC/CAA</td>
</tr>
<tr>
<td>ULRD/AA</td>
<td>83/13</td>
<td>47/11</td>
<td>15/10</td>
</tr>
<tr>
<td>Age &lt; 18 / age ≥ 18</td>
<td>81/15</td>
<td>35/23</td>
<td>10/15</td>
</tr>
<tr>
<td>Male/Female</td>
<td>55/41</td>
<td>31/27</td>
<td>13/12</td>
</tr>
<tr>
<td>Right/Left sided prosthesis users</td>
<td>39/57</td>
<td>19/36 (+3 bilateral)</td>
<td>8/16 (+1 bilateral)</td>
</tr>
<tr>
<td>Participants only in this study</td>
<td>72</td>
<td>24</td>
<td>7</td>
</tr>
<tr>
<td>Participants that took part in the other 2 studies</td>
<td>8 in II &amp; III 16 in II</td>
<td>8 in I &amp; III 16 in I 10 in III</td>
<td>8 in I &amp; II 10 in II</td>
</tr>
<tr>
<td>Total no. of participants in this study</td>
<td>96</td>
<td>58</td>
<td>25</td>
</tr>
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</table>
Prosthesis users who attend the LDAPC are from different counties in Sweden, whereas prosthesis users who attend the CAA are mainly from the Stockholm region. The participants were fitted with one (unilateral) or two (bilateral) prosthetic hands of different sizes and models. Higher-level prosthesis users were fitted with mechanical shoulder or elbow joints. A total of 103 UL prosthesis users took part in the 3 studies, and 34 of them took part in more than one study. Studies II and III were initiated at the same time; therefore 18 prosthesis users took part in both studies.

In Study I, the sample comprised novice prosthesis users (n = 22) and users who had been wearing a myoelectric prosthesis for a period of 3 months to 19 years. All participants joined the study during their regular visits to the LDAPC.

In Study II, to examine the influence of activity on different types of users, prosthesis users with different characteristics were included: (i) different prosthetic levels (transhumeral, transradial, carpal); (ii) different years of prosthetic experience (0–40 years); and (iii) persons with ULRD, persons with AA, both sexes, both prosthetic sides, and persons of different ages (see Table 1). To assure that the sample was evenly distributed with regard to all activities, a ‘minimization’ sampling procedure was applied (see Data collection procedures for details).

Study III aimed to examine the stability of the ACMC ability measures over time; therefore, we tried to recruit prosthesis users with stable control of their prostheses. A sample used for a test-retest study must be stable in terms of the attribute measured by the instrument so that errors from the instrument itself or the measurement procedure can be estimated. Prosthesis users excluded from recruitment were (i) novice prosthesis users or those just fitted with a new prosthesis, (ii) those who were unable to revisit the clinic within 5 weeks for the retest session, and (iii) those who underwent prosthetic training between the test and retest sessions.

### 3.3 Materials in Study IV

Published articles that used outcome measures to evaluate functional outcomes among UL prosthesis users were searched in the AMED, CINAHL, and MEDLINE databases. All English publications dated from 1985 onward, excluding conference proceedings, were considered. A total of 211 studies were found, and 68 studies remained after the removal of duplicates.
3.4 Data collection procedures

Procedures for data collection in Studies I, II and III are presented in Table 2. The ACMC assessments were performed either live (Study I) or with video-recording (Studies II, III). All raters in the studies had taken the ACMC training course and were able to follow the manual to score the participants.

Table 2: Data collection procedures of Studies I-III

<table>
<thead>
<tr>
<th>STUDY</th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activities</td>
<td>Client-chosen</td>
<td>Standardized</td>
<td>Standardized</td>
</tr>
<tr>
<td>Activities per participant</td>
<td>1-2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>No. of visits</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Setting</td>
<td>Live</td>
<td>Recording</td>
<td>Recording</td>
</tr>
<tr>
<td>ACMC Raters (n)</td>
<td>4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Clinical experience of ACMC raters (years)</td>
<td>2,10,15,20</td>
<td>5</td>
<td>5,15</td>
</tr>
</tbody>
</table>

Study I

Self-chosen, non-standardized activities were used for Study I. Each participant was assessed by his/her OT (ACMC rater), who was responsible for the participant’s visit. Six out of 96 ACMC assessments were collected by two OT students under OT supervision (the OT approved the student’s ratings). Client-chosen activities were used for the assessments, such as preparing a simple meal, making a bed, doing crafts, or playing with toys. The rater wrote down the scores on an ACMC 30-item scoring sheet. Missing ratings were allowed in data collection and therefore if an item was not performed during the activity, the item was then considered to be ‘missing.’

Study II

Standardized activities were developed and used in Studies II. ACMC raters from different countries were asked to give three activity suggestions. From the suggestions, six bimanual activities were selected for standardization: ‘repotting a plant,’ ‘a ready-to-assemble project’ (e.g., build a structure with LEGO bricks or assemble a table lamp), ‘setting a table for four persons,’ ‘mixing a store-bought cake/pudding mix,’ ‘sorting bills or pictures,’ and ‘packing a suitcase for an overnight stay.’ The activity steps in each activity were then standardized with the ACMC items, such as opening a double door at shoulder level in all six activities so that the item ‘grasping and releasing in
different positions’ could be observed in all six activities. Activity materials were selected according to the size of the prosthetic hand so that the objects could fit well inside the prosthetic hand.

The allocation method ‘minimization’\textsuperscript{143} was used to assign three of the six standardized activities to each participant so that each activity was performed by a group of prosthesis users with similar characteristics (age, sex, prosthetic side, and prosthetic experience). An OT (n = 3) gave instructions about the activity procedures. All three activities were performed during one clinical visit, and the performances were recorded. In the beginning of using ACMC version 2.0, the rater (Lindner HY) and the ACMC developer (Hermansson LM) assessed a number of participants together to ensure an understanding of the revised rating scale. Thereafter, the rater assessed the participants one activity at a time. A total of 30 ACMC assessments were collected for each activity (6 activities × 30 assessments = 180 assessments).

Study III
Each participant performed one standardized activity approximately 2 to 5 weeks apart. The same OT (n = 6) placed the materials in the same locations and gave activity instructions in both sessions. All performances were recorded. Rater 1 (doctoral student, 5 years of clinical experience) and Rater 2 (ACMC rater, 15 years of clinical experience) assessed each session separately using ACMC version 2.0. For the purpose of intrarater agreement, Rater 1 assessed the test session videos twice, 3 to 4 weeks apart.

Study IV
Two criteria were used to select outcome measures: (i) outcome measure designed to evaluate UL prosthetic functional outcome, such as function, acceptance, usage, satisfaction, adaptation, and ability; and (ii) outcome measure that had been validated with UL prosthesis users. Outcome measures were excluded from consideration if their psychometric evaluations had not been performed with UL prosthesis users.

3.5 Data analyses
Different statistical methods were used in Studies I, II and III (Table 3). The Rasch measurement approach was primarily used in Studies I and II, and the reliability statistical methods were primarily used in Study III. Two different Rasch models (RSM in Study I and MFRM in Studies II, III) were used for data analyses. Both RSM and MFRM are unidimensional models and are appropriate to analyze a set of items that share a common rating scale.\textsuperscript{111} The RSM analyzes two variables, such as item and person, whereas the MFRM
can analyze multiple variables (or facets) simultaneously (item/person/activity in Study II). Because two models and different parameters were used in Studies I-III, the methods are described below separately.

### Table 3: Statistical methods used in Studies I, II and III

<table>
<thead>
<tr>
<th>STUDY</th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics</td>
<td>Item fit statistics</td>
<td>t-test</td>
<td>Weighted κ</td>
</tr>
<tr>
<td></td>
<td>Rating scale analysis</td>
<td>Bias-interaction analysis</td>
<td>PA</td>
</tr>
<tr>
<td></td>
<td>Item difficulty hierarchy</td>
<td></td>
<td>ICC</td>
</tr>
<tr>
<td></td>
<td>PCA</td>
<td></td>
<td>Bland-Altman plot</td>
</tr>
<tr>
<td></td>
<td>DIF and its effect on</td>
<td></td>
<td>SEM</td>
</tr>
<tr>
<td></td>
<td>item difficulty hierarchy</td>
<td></td>
<td>MDC</td>
</tr>
<tr>
<td>Software</td>
<td>Winsteps</td>
<td>SPSS, Facets</td>
<td>SPSS, Facets</td>
</tr>
</tbody>
</table>

*The abbreviations in the table are explained in the following sections*

#### 3.5.1 Study I

Using Winsteps, the RSM calibrated two measures: participant ability measures and item difficulty measures. Each measure has a standard error (SE) that shows its precision. The size of the SE is most strongly influenced by the number of observations used to estimate the measure. The more data given to an item, the higher the precision and hence the lower the SE.

### Technical quality of ACMC items (content)

Item technical quality was examined using infit and outfit fit statistics. Infit is an information-weighted mean-square (MnSq) statistic, and outfit is an unweighted MnSq statistic. MnSq fit statistics show the size of the randomness, and the significance of MnSq is reported by Z-standardized (Zstd) statistics. It has been recommended that an acceptable range to interpret item fit is MnSq of 0.5–1.5 and Zstd of <2.0. Therefore, these criteria were chosen to interpret item fit. An item was considered as a ‘misfit’ if its MnSq was <0.5, which indicates that the item could be redundant, or if its MnSq was >1.5, which indicates the item has been scored inconsistently and further investigation is therefore needed.

### Rating scale functioning (response processes)

The 4-point rating scale was analyzed using Linacre’s guidelines:
- ‘Frequency of Use’ of each rating category was used to indicate the number of participants rated in that particular category.
‘Observed Person Measures’ should increase from a category representing low ability to a category representing high ability.

‘Threshold Measure’ is the transition point between two adjacent categories where there is a 50% chance to select either one of them. The threshold measure should also increase with increasing rating category number. This indicates that each rating category in turn is more likely to be observed than any other rating category as the person’s ability increases. Failure to demonstrate ordered thresholds indicates that the choices in the rating scale do not follow the expected hierarchical ordering.95

Outfit MnSq for each rating category was used to determine the presence of idiosyncratic use of the categories. A rating category with an outfit MnSq of >2.0 indicates that highly unexpected ratings in this category.

Item difficulty hierarchy (response processes)
The difficulty measures of all ACMC items were plotted along a logit scale according to difficulty. In a similar way, the participants were also plotted along the same logit scale according to ability. This logit scale with both persons and items together was used to examine whether item difficulty hierarchy matched clinical experience and whether the item difficulty range was well targeted to the ability range of the participants.

Unidimensionality (internal structure)
The Rasch dimension was first removed from the data. Then, principal components analysis (PCA) examined the contrasts in the residuals. High contrast indicates the strength of many items, suggesting a second dimension.147 PCA also reports the variance explained by the Rasch measures and the variance explained by item difficulties.147 It is considered as good if variance explained by Rasch measures is > 60% and the first contrast is <5%.109

Differential item functioning (DIF) (internal structure)
The existence of DIF was investigated in two person characteristics: sex and prosthetic side. A noticeable item DIF is present if the DIF size is >0.5 logits and is significant (t-statistic, \( p < 0.05 \)).147, 149 The influence of DIF was further investigated in the item difficulty hierarchy. The two item difficulty hierarchies in each subgroup (such as male against female) were compared.

3.5.2 Study II

Prosthetic wearing time and hand dominance (relations to other variables)
Mean ability measures of full-time and non-full-time prosthesis users were calculated. Similarly, mean ability measures of dominant-sided/non-
dominant-sided prosthesis users were also calculated. Then independent $t$-test was used to test the differences between the means of full-time/non-full-time prosthesis users and dominant-sided/non-dominant-sided prosthesis users.

**Influence of activities (construct-irrelevant variance)**
Using FACETS software\(^{150}\) the MFRM calibrated three facets: participant ability measure, item difficulty measure, and activity difficulty measure. Two analyses were then performed: (i) investigation of the activities in relation to the user ability; and (ii) investigation of the sex and prosthetic side in relation to the activities. For the first investigation, the hypothesis was that participants would perform similarly in their assigned activities and hence get similar ability measures. The bias-interaction analysis produced a bias size that indicated whether any participant performed differently in any activity compared with the mean participant ability measure. For the second investigation, a bias size was generated for the interaction between each activity and each user characteristic. Separate analyses of persons with ULRD and with AA were performed. The magnitude of the bias size indicated whether an activity was harder or easier for any sex or prosthetic side compared with the activity difficulty measure based on the whole sample. The significance of each interaction was tested with the $t$-statistic. As suggested by the MFRM, an interaction was considered significant when the magnitude of the bias size was $\geq \pm 0.5$ logits and the interaction was statistically significant ($p < 0.05$).\(^{149,151}\)

### 3.5.3 Study III

**Test-retest reliability**
Test-retest reliability was examined using three different statistics. Agreement at the item level was examined using the quadratic weighted kappa (weighted $\kappa$) and percentage agreement (PA). Participant ability measures for each session (estimated using FACETS software\(^{150}\)) were used to calculate the intraclass correlation coefficient (ICC\(_{2,1}\)). The Bland-Altman method was used to examine the agreement between participant ability measures in both sessions. The standard error of measurement (SEM) was calculated to show the amount of measurement error from both sessions. Three SEMs were calculated: one for Rater 1, one for Rater 2, and one for both raters together. The SEMs were then used to determine the MDC at the 95% confidence level (MDC\(_{95}\)), again one for each rater and one for both raters together.

**Rater reliability**
Inter-rater agreements of ACMC version 2.0 were examined for each session separately. At the item level, weighted $\kappa$ and PA were used. Participant ability
measures from each rater were used to calculate two ICC\textsubscript{2,1}, one for each session. Intrarater agreement of Rater 1 was also examined using weighted \( \kappa \), PA and ICC\textsubscript{3,1}. 

### 3.5.4 Study IV

Eight prosthetic outcome measures had been validated with UL prosthesis users at the time of this study. Apart from the University of New Brunswick (UNB) test, all identified outcome measures had at least one published psychometric study, giving a total of 14 published psychometric studies. The UNB test only briefly reports its rater reliability evaluation in its manual\textsuperscript{152} and the information is not sufficient to assess its methodology. Methodology appraisal was therefore conducted on 14 studies separately by two reviewers (the doctoral student and the second author) using an appraisal form by MacDermid\textsuperscript{153} The MacDermid appraisal form has been used to rate the qualities of psychometric studies in different recent systematic reviews in other clinical fields.\textsuperscript{154-156} Any disagreement between the two reviewers was discussed with the third author until a consensus was reached.

The linking process was performed in several steps. (i) The items/questions in each outcome measure were entered into Excel. There were 438 items/questions in the 8 outcome measures, and some items were common in the different age or parent/child versions of the same measure. (ii) A total of 369 items/questions remained after the removal of duplicates of the same measure. (iii) Extraction of meaningful concepts from each item/question was then performed based on the ICF linking rules and advice from the ICF team leader Dr. Cieza. According to the ICF linking rules,\textsuperscript{136, 157, 158} more than one meaningful concept can be extracted from one item/question; e.g., two concepts were extracted from the ACMC item ‘coordinating both hands during grasping,’ namely ‘hand coordination’ and ‘grasping.’ (iv) Each meaningful concept was then linked to an ICF category based on the ICF category definition. For example,

\begin{quote}

‘Grasping’ was linked to the ICF category ‘d4401 Grasping’ – which is defined as using one or both hands to seize and hold something, such as when grasping a tool or a door knob.\textsuperscript{159}
\end{quote}

(v) Excel was used to calculate the frequencies of concepts and ICF categories used for each component.
4 Ethical Considerations

Study I was approved by the Ethics Research Committee at Örebro County Council and Studies II-III was approved by Uppsala Ethical Committee. Study IV does not need ethical approval based on decision from the Regional Ethics Committee review board of Uppsala.

All the participants and the parents for participants under 18 have received written and verbal information about the studies and about their rights to withdrawal and anonymity before participation. Parental written consent was obtained after parents had agreed to allow their child to participate in the studies. Although parents have decision-making power when their children are the object of research, the children should also have the right to decide when they are capable of understanding what consent to being researched means. Hence, both participants under 18 and their parents received written and verbal information but the parents were the ones who signed the consensus.

Asking UL prosthesis users to perform activities is a normal routine at both clinics. In Study I, the assessments were taking place when the participants were performing activities of their own choices, such as playing with toys or cooking or performing other activities. However, standardized activities were used in Study II and III, that is, these activities were not client-chosen. We informed each participant about the activities they would have to perform so that they were able to consider if they would like to participate in Study II and III. For younger children, all the activities were adjusted to become a play activity, such as packing a doll outfit in a small colorful suitcase, setting table for a tea party, or opening envelopes with colorful stickers.

One major ethical consideration is the use of video-recording for data collection in Study II and III. Therefore, we explained carefully where the videos would be stored and no irrelevant person will have access to them. All information of the participants was kept confidential and it is not possible to identify any participant from the data. It can happen that some participants may feel that their integrities are intruded after their performances were recorded. Therefore, it was strongly emphasized that they could retrieve from their participation at any time. During data collection, no participant had retrieved their participation and some of them even asked for copies of their videos.
5 Results

5.1 Content, response processes, internal structure evidence (Study I)

5.1.1 Technical quality of ACMC items

Of 30 items, 27 were found to have MnSqs of 0.5 to 1.5. Two items were found to have an MnSq of >1.5 (with Z > 2.0). They were scored higher than expected according to the Rasch model in the three assessments, and their MnSqs were within 0.5 - 1.5 after removing the three assessments. This finding suggested that the item misfit was not systematic to the items. One item was found to have MnSq of <0.5 (with Z > 2.0); which suggested that this item could be redundant.

5.1.2 Rating scale functioning

Table 4. Summary statistics for the 4 rating-scale categories

<table>
<thead>
<tr>
<th>Rating Category</th>
<th>Frequency of Use (%)</th>
<th>Observed Person Measure</th>
<th>Threshold Measure</th>
<th>Outfit MnSq</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - not capable</td>
<td>388 (19)</td>
<td>-3.07</td>
<td>None</td>
<td>1.14</td>
</tr>
<tr>
<td>1 - sometimes capable</td>
<td>380 (18)</td>
<td>-0.69</td>
<td>-1.72</td>
<td>1.00</td>
</tr>
<tr>
<td>2 - capable on request</td>
<td>366 (18)</td>
<td>1.10</td>
<td>0.31</td>
<td>0.50</td>
</tr>
<tr>
<td>3 - spontaneously capable</td>
<td>949 (46)</td>
<td>3.90</td>
<td>1.41</td>
<td>1.09</td>
</tr>
</tbody>
</table>

Summary statistics for the four rating scale categories are shown in Table 4. The ‘frequency of use’ among categories 0, 1, and 2 was fairly even. Category ‘3 - spontaneously capable’ was used approximately three times more often than any of the other three categories. Both the observed person measures and threshold measures increased with the rating category value. Outfit MnSq for all categories was ≤1.14, indicating that there was no idiosyncratic use of the categories. All of these results suggest that the rating scale functioned in the expected manner.

Outfit MnSq for Category ‘2 - capable on request’ was 0.50, however, indicating that the use of this category was somewhat redundant. Use of rating category 2 is clearly visualized in Fig. 8. The plot shows how the rating scale
categories relate to the underlying construct. Compared with the rating categories 0, 1, and 3, the width of category 2 occupies a relatively small range along the x-axis, indicating that the use of category 2 was somewhat redundant (Fig. 8).

![Fig.8. The probability curves of the 4 ACMC rating categories. The 0, 1, 2 and 3 category curves on the graph represent the 4 ACMC rating categories. The x-axis is participant ability minus item difficulty in logits.](image)

5.1.3 Item difficulty hierarchy and targeting

The item difficulty hierarchy and its relationship with the participants’ abilities are shown in Fig. 9. Less capable persons/easier items are located at the lower end, while more capable persons/more difficult items are located at the upper end. Items that assess ‘the need for visual feedback’ during repetitive grip, repetitive release, and adjust force were the most difficult items. The items that assess timing were also difficult. Items that assess the need for external support were the easiest items. Thus, the item difficulty matched the clinical experience in terms of the difficulty of items. The items targeted well the ability of the sample (By default, mean item difficulty = 0 logits; mean participant ability = +0.48 logits). However, several items that assessed visual feedback and timing had >50% missing ratings and slightly high SE (0.23–0.33).

5.1.4 Unidimensionality and presence of DIF

Statistical decomposition of the variance in data indicates that the variance explained by the Rasch measures was 78% (not published), whereas 30.2% of the variance was explained by the item difficulties. The first factor in the residuals explained 2.3% of the variance in the data. The analysis of DIF showed that no item exhibited DIF between subjects with right or left pros-
thesis. Of the 30 items, 3 exhibited DIF between males and females. Furthermore, two of the DIF items had >50% missing ratings. When comparing the male and female item hierarchies, these three items maintained similar locations along the respective item difficulty hierarchies.

<table>
<thead>
<tr>
<th>Logit scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
</tr>
<tr>
<td>X</td>
</tr>
<tr>
<td>7</td>
</tr>
</tbody>
</table>

| X | + |
| X | |
| X | |
| 6 |

| XX | T+ |
| X | |
| X | |
| X | |
| 5 |

| + | |
| X | |
| XX | |
| X | |
| 4 |

| +T |
| XXX | |
| X | |
| XX | Sl |
| XXX | G-repetitive grip, without visual feedback |
| 3 | 

| XXX | G-adjust force, without visual feedback R-repetitive release, without visual feedback |
| XX | G-object towards hand |
| XXXXXXX | G-feed hand forward |
| XXX | G-without visual feedback |
| 2 |

| XX | +S |
| XXX | |
| XX | |
| XXX | C-when gripping R-same time, arms in motion R-timing, arm is in forward/upward position |
| XXXX | R-timing, arm is in low position |
| 1 |

| XXXX | + |
| X | |
| XXXX | MI |
| XXX | R-adjust opening width |
| 0 |

| XX | +M |
| XXX | G-repetitive grip H-in motion, without visual feedback R-repetitive release |
| XX | R-without visual feedback |
| XXX | G-adjust force when gripping G,R-in any position H-w/out crushing H-w/out visual feedback |
| X | |
| | -1 |

| XXX | + |
| XXX | H-in motion |
| XX | G-tripod pinch, without support R-without support |
| X | |
| | -2 |

| X | +S |
| XXX | G-whole hand, without support |
| XX | |
| XXX | G-tripod pinch, with support |
| X | H-without support |
| XXX | |
| | -3 |

| XXX | + |
| XX | H-with support |
| XXX | G-with support |
| X | R-with support |
| | -4 |

| X | +T |
| XX | |
| | |
| | -5 |

| XX | + |
| T | |
| X | |
| | |
| | -6 |

| + | |

---

Figure 9. Persons' ability measures in relation to item difficulty measures. X= participant, M= mean for participant ability and item difficulty, S= 1 Standard deviation (SD) from the mean, T= 2 S.D. from mean, G= gripping, R= releasing, H= holding, C= co-ordinating, w/out= without
5.2 From version 1.0 to version 2.0

Based on the findings in Study I, a revision of the ACMC was performed before Studies II-IV were initiated. The revision was intended to both improve the test in terms of evidence for validity and increase the usability of the test for clinicians. First, the findings on rating scale functioning were discussed with the Study I raters. Category ‘2 - capable on request’ was somewhat redundant because (i) some raters did not see the need to give a verbal request or (ii) the rater had missed the chance to give a verbal request. To improve the overall functioning of the rating scale, a decision was made to remove the verbal request and physical/verbal guidance from the middle categories. The category names and definitions were reworded to clearly indicate the increasing capacity level (Table 5).

Table 5: The ACMC rating scale

<table>
<thead>
<tr>
<th>Version 1.0</th>
<th>Category</th>
<th>Version 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spontaneous and skillful control</strong></td>
<td></td>
<td><strong>Extremely capable</strong></td>
</tr>
<tr>
<td>The item is performed smoothly and skillfully.</td>
<td></td>
<td>Same as in version 1.0</td>
</tr>
<tr>
<td>The use of the prosthetic hand is immediate and</td>
<td></td>
<td></td>
</tr>
<tr>
<td>spontaneous</td>
<td></td>
<td></td>
</tr>
<tr>
<td>**Capable on request, spontaneity is not</td>
<td></td>
<td><strong>Generally capable</strong></td>
</tr>
<tr>
<td>established**</td>
<td></td>
<td>Able to perform the item but the quality of</td>
</tr>
<tr>
<td>The use of prosthetic hand is not</td>
<td></td>
<td>movement is questionable. The use of the</td>
</tr>
<tr>
<td>spontaneous and verbal request is needed.</td>
<td></td>
<td>prosthetic hand can be</td>
</tr>
<tr>
<td>The person is capable to perform the particular</td>
<td></td>
<td>slightly delayed</td>
</tr>
<tr>
<td>item but the control is delayed and not</td>
<td></td>
<td></td>
</tr>
<tr>
<td>skillful</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sometimes capable, stability in the control is</strong></td>
<td></td>
<td><strong>Somewhat capable</strong></td>
</tr>
<tr>
<td>not established**</td>
<td></td>
<td>The item is performed with difficulty or</td>
</tr>
<tr>
<td>Physical or verbal guidance is needed. The</td>
<td></td>
<td>sometimes fails.</td>
</tr>
<tr>
<td>control is slow, awkward and often fails</td>
<td></td>
<td>The use of the prosthetic hand can be</td>
</tr>
<tr>
<td></td>
<td></td>
<td>significantly delayed</td>
</tr>
<tr>
<td><strong>Not capable</strong></td>
<td></td>
<td><strong>Not capable</strong></td>
</tr>
<tr>
<td>Cannot perform the item even after several</td>
<td></td>
<td>Same as in version 1.0</td>
</tr>
<tr>
<td>attempts or do not attempt to perform the item at</td>
<td></td>
<td></td>
</tr>
<tr>
<td>all</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cannot rate the item</strong></td>
<td></td>
<td><strong>Cannot rate the item</strong></td>
</tr>
<tr>
<td>The item is not observed</td>
<td></td>
<td>Same as in version 1.0</td>
</tr>
<tr>
<td>Version 1.0</td>
<td>Version 2.0</td>
<td></td>
</tr>
<tr>
<td>-------------------------------------------------</td>
<td>-------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>The need for external support</td>
<td>The need for external support</td>
<td></td>
</tr>
<tr>
<td>G - whole hand, with support&lt;sup&gt;1&lt;/sup&gt;</td>
<td>Grasping with support&lt;sup&gt;1&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>G - tripod pinch, with support&lt;sup&gt;1&lt;/sup&gt;(redundant)</td>
<td>Power grip, without support</td>
<td></td>
</tr>
<tr>
<td>G - whole hand, without support</td>
<td>Precision grip, without support</td>
<td></td>
</tr>
<tr>
<td>G - tripod pinch, without support</td>
<td>Holding with support</td>
<td></td>
</tr>
<tr>
<td>H - with support</td>
<td>Holding without support</td>
<td></td>
</tr>
<tr>
<td>H - without support</td>
<td>Releasing with support</td>
<td></td>
</tr>
<tr>
<td>R - with support</td>
<td>Releasing without support</td>
<td></td>
</tr>
<tr>
<td>R - without support</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grip force and Opening width</td>
<td>Grip force and Opening width</td>
<td></td>
</tr>
<tr>
<td>Adjusting force when gripping</td>
<td>Appropriate grip force</td>
<td></td>
</tr>
<tr>
<td>Holding without crushing</td>
<td>Holding without crushing</td>
<td></td>
</tr>
<tr>
<td>Adjust opening width</td>
<td>Adjust opening width</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coordination of both hands</td>
<td>Coordination of both hands</td>
<td></td>
</tr>
<tr>
<td>C - when gripping</td>
<td>Coordinating both hands during grasping</td>
<td></td>
</tr>
<tr>
<td>C - when releasing&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Coordinating both hands during releasing&lt;sup&gt;2&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Different positions and in motion(timing)</td>
<td>Different positions and in motion (timing)</td>
<td></td>
</tr>
<tr>
<td>G - in any position</td>
<td>Grasping in different positions</td>
<td></td>
</tr>
<tr>
<td>R - in any position</td>
<td>Releasing in different positions</td>
<td></td>
</tr>
<tr>
<td>G - move hand forward&lt;sup&gt;3&lt;/sup&gt;</td>
<td>Timing during grasping&lt;sup&gt;3&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>G - object towards hand&lt;sup&gt;3&lt;/sup&gt;</td>
<td>Timing during releasing&lt;sup&gt;4&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>R - same time, arms in motion&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Holding in motion</td>
<td></td>
</tr>
<tr>
<td>R - timing, arm in forward/upward position&lt;sup&gt;4&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R - timing, arm in low position&lt;sup&gt;4&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H - in motion</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Repetitive grasp and release</td>
<td>Repetitive grasp and release</td>
<td></td>
</tr>
<tr>
<td>Repetitive grip&lt;sup&gt;5&lt;/sup&gt;</td>
<td>Repetitive grip&lt;sup&gt;5&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Repetitive release&lt;sup&gt;5&lt;/sup&gt;</td>
<td>Repetitive release&lt;sup&gt;5&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The need for visual feedback</td>
<td>The need for visual feedback</td>
<td></td>
</tr>
<tr>
<td>G – without visual feedback</td>
<td>Grasping without visual feedback</td>
<td></td>
</tr>
<tr>
<td>G - Adjust force, without visual feedback</td>
<td>Appropriate grip force without visual feedback</td>
<td></td>
</tr>
<tr>
<td>H - without visual feedback</td>
<td>Holding without visual feedback</td>
<td></td>
</tr>
<tr>
<td>H - in motion, without visual feedback</td>
<td>Holding in motion, without visual feedback</td>
<td></td>
</tr>
<tr>
<td>R - without visual feedback</td>
<td>Releasing, without visual feedback</td>
<td></td>
</tr>
<tr>
<td>G - repetitive grip, without visual feedback&lt;sup&gt;6&lt;/sup&gt;</td>
<td>Repetitive grasp and release, without visual feedback&lt;sup&gt;6&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>R - repetitive release, without visual feedback&lt;sup&gt;6&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>G</sup>-gripping, <sup>H</sup>-holding, <sup>R</sup>-releasing, <sup>C</sup>-coordinating. Number in superscript - Items with the same number in version 1.0 are combined to become one item with the same number in version 2.0.
Next, the high missing ratings in several items (visual feedback and timing items) were discussed with the raters. As also discussed in the first validity assessment of the ACMC, some raters were confused between the use of category ‘0 – not capable’ and ‘missing’ in certain difficult items, such as visual feedback and timing. Therefore, a decision was made to combine these difficult, closely related items and redefine other items that were misinterpreted with the assumption that this would reduce the confusion. The redundant item ‘G - tripod pinch, with support’ was combined with ‘G - whole hand, with support.’ Many of the items were also renamed in version 2.0 (e.g., ‘G - tripod pinch, without support’ in version 1.0 and ‘Precision grip, without support’ in version 2.0 are the same items but with different names). This version 2.0 with 24 items was used in Study IV (Table 6).

After using version 2.0 during the years 2009–2010, a slight revision was made. At that time, it was found that the item ‘adjust opening width’ was rated inconsistently. Another item, ‘holding without crushing,’ was considered similar to ‘appropriate grip force.’ These two items had exactly the same difficulty measure in the analysis from Study I. Therefore, version 2.0 became a 22-item version and was used in Studies II and III.

5.3 Relations to other variables & construct-irrelevant variance (Study II)

5.3.1 Relations to prosthetic wearing time & hand dominance
For both groups (ULRD and AA), the mean ability measures of full-time prosthesis users were significantly higher than that of non-full-time users (ULRD $p = 0.04$, AA $p = 0.04$). Participants with dominant-sided AA had higher ability measures than those with non-dominant-sided AA ($p = 0.01$), whereas no significant difference between sides was found in participants with ULRD.

5.3.2 Influence of standardized activities
Of the 60 prosthetic hands from 58 users (the 2 bilateral users with 2 myoelectric hands gave 4 ACMC assessments), 57 showed no significant differences among their 3 assessments, and their ability measures showed a difference of <0.5 logits. Three non-full-time prosthetic users had different ability measures (>0.5 logits), and the differences were significant.

The difficulty range of the six activities was between −0.67 and −1.08 logits; that is, they were similar in terms of difficulty. The analyses between the activities across sex and prosthetic side showed that the bias sizes of the activities were all within ±0.5 logits and did not differ significantly between males.
and females ($p ≥ 0.17$) or between dominant and non-dominant prosthesis users (ULRD $p ≥ 0.59$; AA $p ≥ 0.33$). This implies that the activities functioned similarly across both subgroups in terms of sex and prosthetic side.

### 5.4 Evidence on test-retest reliability and rater agreement (Study III)

The mean ability measure was 0.97 logits (test session) and 0.96 logits (retest session) respectively. For test-retest reliability, the weighted $\kappa$ of all items was 0.52 to 1.00 (PAs 66%–100%), and the test-retest ICC$_{2,1}$ was 0.94. One item was scored with one rating category, and hence no weighted $\kappa$ was calculated. The Bland-Altman method showed that all but one participant, a non-full-time prosthesis user, were within the 95% LOA. The MDC$_{95}$ was 0.52 logits (Rater 1), 0.55 logits (Rater 2), and 0.69 logits (both raters). All MDC$_{95}$ were <5% of the total ability logit range.

For inter-rater agreement, three items were scored with one rating category only, and hence no weighted $\kappa$ was calculated. The weighted $\kappa$ at the item level in both sessions was 0.44 to 1.00 (PAs 56%–100%), and the ICC$_{2,1}$ was 0.95 (test) and 0.92 (retest), respectively. Among all items, the two items ‘grasping’ and ‘releasing’ without visual feedback had the lowest PA and weighted $\kappa$. For the intrarater agreement of Rater 1, the weighted $\kappa$ at the item level were all >0.80 and their PAs were ≥96%. The ICC$_{3,1}$ for the test session of Rater 1 was 0.98.

### 5.5 Content comparison using ICF (Study IV)

Eight outcome measures and 14 psychometric studies were found (in 2009):

- ACMC – all ages $^4, 127, 160$
- Child Amputee Prosthetics Project - Functional Status Inventory (CAPP-FSI) - age 1 to 17$^{161-163}$
- Child Amputee Prosthetics Project - Prosthesis Satisfaction Inventory (CAPP-PSI) - age 1 to 17$^{164}$
- Orthotics and Prosthetics Users’ Survey (OPUS) - all ages but only one module has been validated with adult UL prosthesis users$^{122}$
- Prosthetic Upper Extremity Functional Index (PUFI) - age 3 to 18$^{22, 165, 166}$
- Trinity Amputation and Prosthesis Experience Scales (TAPES) - adults $^{167}$
- Unilateral Below Elbow Test (UBET) - age 2 to 21$^{166, 168}$
- University of New Brunswick test (UNB) - age 2 to 21$^{152}$ (test manual)

Three observational measures are clinician-used (ACMC, UBET, and UNB). The ACMC uses client-chosen activities for assessment, whereas the UBET and the UNB test assess prosthetic control with activities for different age
groups. The other five are client-rated questionnaires (CAPP-FSI, CAPP-PSI, OPUS, PUIFI, and TAPES) that evaluate prosthesis use in daily life. Appraisal of the study methodologies showed that all studies received more than 60% of the ratings, and more than 80% of the ratings were given to the ACMC, OPUS, and TAPES.

In terms of primary focus, the CAPP-FSI, CAPP-PSI, OPUS, PUIFI, and UBET primarily focus on evaluation of function or functional status in prosthesis users, but their questions/items cover different areas. For example, the OPUS has questions on quality of life, the TAPES focus on psychosocial adjustment, and the CAPP-PSI has questions on prosthetic component functions.

A total of 393 concepts were extracted from 369 items/questions. The concepts were linked to 54 ICF categories. The frequencies of the ICF categories used in ‘Body Functions,’ ‘Activity and Participation,’ and ‘Environmental Factors’ are presented in Tables 7, 8, and 9. The ACMC, OPUS, and TAPES have concepts that linked exclusively to the ‘Body Function’ categories, such as coordination and emotional functions (Table 7).

Table 7. Frequencies of ICF categories used in ‘Body functions’

<table>
<thead>
<tr>
<th>ICF categories in ‘Body functions’</th>
<th>ACMC</th>
<th>CAPP-FSI</th>
<th>CAPP-PSI</th>
<th>OPUS</th>
<th>TAPES</th>
<th>PUIFI</th>
<th>UBET</th>
<th>UNB</th>
</tr>
</thead>
<tbody>
<tr>
<td>b1300 Energy level</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b1400 Sustaining attention</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b152 Emotional functions</td>
<td></td>
<td>10</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b1801 Body image</td>
<td></td>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b28014 Pain in upper limb</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b28014 Pain in lower limb</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b7602 Co-ordination of voluntary</td>
<td>8</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>movements of the skin</td>
<td>1</td>
<td></td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>

Seven outcome measures, except the CAPP-PSI, were linked to the categories in ‘Activity and Participation’ (Table 8). As UL prosthesis is replacement of the missing hand, the categories ‘fine hand use’ and ‘hand and arm use’ had the highest frequencies. The highest frequency is the UNB test because it has the highest number of activities. Although the TAPES is designed for both UL and lower limb users, it’s activities are related to more frequent to lower limb use than upper limb use. The CAPP-PSI questions are all focused on services and prosthetic components, and they are thus linked with the categories in the component ‘Environmental Factors.’ The OPUS and TAPES also have a specific module that evaluates prosthesis services, and they were linked to categories in ‘Environmental Factors’ (Table 9).
### Table 8. Frequencies of ICF categories used in Activity and Participation

<table>
<thead>
<tr>
<th>ICF categories in Activity and participation</th>
<th>ACMC</th>
<th>CAPP-FSI</th>
<th>CAPP-PSI</th>
<th>OPUS</th>
<th>TAPES</th>
<th>PUF1</th>
<th>UBET</th>
<th>UNB</th>
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<tr>
<td>d170 Writing</td>
<td>1</td>
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<tr>
<td>d2100 Undertaking a simple task</td>
<td>32</td>
<td>11</td>
<td>26</td>
<td>23</td>
<td>66</td>
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<tr>
<td>d230 Carrying out daily routine</td>
<td>3</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>d350 Conservation</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d430 Lifting and carrying objects</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td>d4300 Lifting</td>
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<td>d4301 Carrying in the hands</td>
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<tr>
<td>d440 Fine hand use</td>
<td>6</td>
<td>32</td>
<td>11</td>
<td>26</td>
<td>23</td>
<td>66</td>
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<td>d445 Hand and arm use</td>
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<td>32</td>
<td>11</td>
<td>26</td>
<td>23</td>
<td>66</td>
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<td>d4401 Grasping</td>
<td>11</td>
<td>1</td>
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<td>d4403 Releasing</td>
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<td>d4450 Pulling</td>
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<td>d4451 Pushing</td>
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<td>d4454 Throwing</td>
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<td>d4455 Catching</td>
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<tr>
<td>d4500 Walking short distances</td>
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<tr>
<td>d4501 Walking long distances</td>
<td>2</td>
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<td>d4551 Climbing</td>
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<td>d4552 Running</td>
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<td>d5201 Caring for teeth</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>d5202 Caring for hair</td>
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<td></td>
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<tr>
<td>d5203 Caring for fingernails</td>
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<td>d5400 Putting on clothes</td>
<td>5</td>
<td>3</td>
<td>6</td>
<td>4</td>
<td>6</td>
<td></td>
<td></td>
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<tr>
<td>d5401 Taking off clothes</td>
<td>5</td>
<td>1</td>
<td></td>
<td></td>
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<td>d5402 Putting on footwear</td>
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<tr>
<td>d5403 Taking off footwear</td>
<td>2</td>
<td>4</td>
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<td></td>
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<tr>
<td>d550 Eating</td>
<td>3</td>
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<td>2</td>
<td>1</td>
<td>3</td>
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<tr>
<td>d560 Drinking</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td>4</td>
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<td>d6300 Preparing simple meals</td>
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<td></td>
</tr>
<tr>
<td>d6301 Preparing complex meals</td>
<td>5</td>
<td>1</td>
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<td></td>
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<td>d640 Doing housework</td>
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<td>d6400 Washing and drying clothes and garments</td>
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<tr>
<td>d6401 Cleaning cooking areas and utensils</td>
<td>1</td>
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<td>d6402 Cleaning living area</td>
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<tr>
<td>d6500 Making and repairing clothes</td>
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<td></td>
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<tr>
<td>d750 Informal social relationships</td>
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<tr>
<td>d850 Remunerative employment</td>
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<tr>
<td>d870 Economic self-sufficiency</td>
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<tr>
<td>d920 Recreation and leisure</td>
<td>1</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>d9201 Sports</td>
<td>1</td>
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<tr>
<td>d9204 Hobbies</td>
<td>1</td>
<td>1</td>
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<td>d9205 Socializing</td>
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</tr>
</tbody>
</table>

### Table 9. Frequencies of ICF categories used in Environmental factors

<table>
<thead>
<tr>
<th>ICF categories in Environmental factors</th>
<th>ACMC</th>
<th>CAPP-FSI</th>
<th>CAPP-PSI</th>
<th>OPUS</th>
<th>TAPES</th>
<th>PUF1</th>
<th>UBET</th>
<th>UNB</th>
</tr>
</thead>
<tbody>
<tr>
<td>e1151 Assistive products and technology for personal use in daily living</td>
<td>4</td>
<td>16</td>
<td>24</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e4 Attitudes</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>e5800 Health services</td>
<td>6</td>
<td>10</td>
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</tr>
</tbody>
</table>

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HELEN LINDNER  
*The Assessment of Capacity for Myoelectric Control*
6 Discussion

6.1 General discussion

Instrument validation is a process that gathers evidence to support the meaning of test scores in relation to their intended use. The current view on validity refers to ‘...evidence and theory in support of the interpretation of test scores...’ The ACMC is designed to measure a theoretical construct that covers six aspects related to the capacity for myoelectric control, all of which have been described in the literature. However, it is possible that ACMC has missed some other aspects related to myoelectric control. Furthermore, advances in prosthetic component design and control formats may lead to new aspects related to myoelectric control, and it is possible that the ACMC may include new aspects in the future. Nevertheless, the aim of this thesis was not to develop an instrument that covers all aspects of this capacity. Instead, the aim was to validate the ACMC and to assess whether any evidence exists in support of its use to assess the ability to control a myoelectric prosthetic hand.

Instead of using different types of validity, different sources of evidence are used as a framework upon which to organize the validations and findings in this thesis. Different researchers have published different validation examples for each source of evidence based on their interpretations. It is therefore possible that readers may also have different interpretations on how the validations are to be organized with respect to the different sources of evidence in this thesis. Nevertheless, the current view on validity is welcomed by researchers and authors in different clinical fields.

A minor but important part of this thesis is a content comparison of UL prosthetic measures. While the comparison was performed to identify the similarities and differences between these outcome measures, the long-term goal of this comparison is to encourage the use of validated outcome measures in clinical practice. The discussion below starts with the findings concerning the psychometric evidence of the ACMC, which is followed by a discussion of the content comparison.

6.2 Validity Evidence of the ACMC (Study I and II)

Evidence based on content evidence often focuses on content relevance and content representativeness, but rarely on technical quality of items such as ‘unambiguous phrasing.’ Examining the item technical quality using Rasch item fit statistics is a fairly new suggestion, but it has been used in a few psy-
Each ACMC item has a detailed definition that guides ACMC raters to rate the item; therefore, a poorly defined item that causes confusion in raters would lead to inconsistent ratings. The results showed that two items had MnSq > 1.5, but this was due to three assessments and was not systematic to the items. Interestingly, in the first validation of ACMC, in which a smaller MnSq was chosen (0.4–1.6), all items showed acceptable fit statistics. This further confirmed that the item misfit in Study I was likely due to sample or even rater error. Because the item misfit was not systematic to the items, and considering the findings from the first validation of the ACMC, we suggest that all items have sufficient technical qualities.

Evidence based on response processes was searched using an item difficulty hierarchy, which provides evidence on how the abilities of prosthesis users demonstrate the construct. From clinical experience, we know that ‘the need for external support’ is the easiest aspect whereas ‘the need for visual feedback’ is the most difficult aspect; therefore, the empirical item difficulty hierarchy is an important piece of evidence. This empirical item difficulty hierarchy has two practical meanings. One is to provide us a sense of how much of the underlying construct or attribute is required to perform the item successfully, and the other is to provide us a picture of how the items are related to one another along the construct. This means that the hierarchy may be used as a guideline to indicate how a typical new prosthesis user can be trained from the easiest aspect, ‘the need for external support,’ all the way up to the most difficulty aspect, ‘the need for visual feedback.’

Evidence based on response processes was also searched by analyzing the rating scale. The overall analysis of the rating scale suggested that the responses to the rating scale behave in the expected manner. Category ‘2 – capable on request’ occupies a shorter range on the construct ‘capacity for myoelectric control’ compared with adjacent categories. This is not a serious problem, but the functioning of this category should ideally be improved. Two suggestions have been raised to improve the functioning of Category 2: (i) collapse Categories 1 and 2 because studies have shown that the collapse of underused categories can improve rating scale functioning, or (ii) revise the definition of Category 2. After a discussion with the raters, it seems that revising the definition is a better choice because the use of a rating category should not depend on whether a rater gives a verbal request or not, although verbal request are often used in prosthetic training. Therefore, the decision was made to revise the rating category definitions and to reword the category names to clearly indicate an increasing level of capacity.
One important validation concerning evidence based on internal structure is the unidimensionality of an instrument. Unidimensionality is fundamental for invariant measurement, meaning that the rank order of item difficulty should not vary from one sample to another sample.⁹¹ The PCA results showed that the ACMC fulfils the requirement to be unidimensional. Together with the earlier evaluation,⁴ unidimensionality is demonstrated twice in the ACMC with two different methods (item fit and PCA). The evidence of unidimensionality thus provides an encouraging starting point for measuring the capacity for myoelectric control. However, DIF was present in three items for males and females. Two of these DIF items had more than 50% missing ratings, and missing ratings reduce item precision (large SE); therefore, it is too early to draw any conclusion regarding whether DIF exists in these items. Furthermore, as suggested in other literature, the sample size for DIF analysis must be at least 100 per group.¹⁴⁹, ¹⁵¹ Therefore, the current finding on DIF can only indicate the possibility of DIF in these items. Further research with a large sample is needed.

Evidence based on relations with other variables is often searched by evaluating the correlation of a given instrument with another similar instrument. Apart from the correlation with another instrument, Messick suggested that ‘other variables’ can be any external variables that are able to support the validity of the instrument.¹⁰⁴ In this thesis, the prosthetic wearing time and hand dominance were chosen as external variables because they are widely used in the prosthetic field to indicate prosthetic acceptance or daily prosthetic use.¹⁹, ⁴⁵, ⁸⁸, ¹¹⁸-¹²² The results showed that full-time prosthesis users had higher ability measures than did non-full-time users among both persons with ULRD and persons with AA. This finding is in accordance with a study in which functionality among children with ULRD was evaluated.⁵⁷ Adaptation to the prosthesis often encourages the users to increase their wearing time.⁵⁷, ¹⁸⁰ This may stimulate patients to use their prostheses in daily activities and hence achieve better myoelectric control; i.e., higher ability measures. For another variable, ‘hand dominance,’ persons with dominant-sided AA had higher ability measures than did those with non-dominant-sided AA. Although there were too few participants with AA in Study II to draw any definite conclusions, dominant-sided prosthesis users are likely to use their prostheses more actively than non-dominant-sided users, and hence a higher ability measure is likely to be observed. Because the results are based on mean differences between groups but not on the correlations between the ACMC ability measures and these two variables, this evidence is not as strong as that based on correlations.
6.3 Influence of activities - construct-irrelevant variance (Study II)

The question of whether activities have any influence on the ability measures has been raised in two ACMC validation studies: once in 2006 and again in Study I. Therefore, six activities were standardized to answer this question. The results showed that in the majority of participants, there was no significant difference among their assessments, and their ability measures showed a difference of <0.5 logits. This confirms that construct-irrelevant variance is always present to some extent. The six standardized activities are similar in some ways but different in others. They are similar in that they all contain everyday objects such as clothing, glasses, kitchenware, table lamps, paper, pens, or LEGO for children. They are also similar because every activity involves objects that require prosthesis users to use their prosthetic hands in different positions and to pass objects between their hands. However, the object shapes and textures are different enough to allow the evaluation of activity influence on the ACMC ability measures. The results showed that the majority of participants received similar ability measures in their assessments while performing different activities. This means that for a user who can control his/her prosthetic hand without the need for external support, he/she is capable of grasping a LEGO piece (a ready-to-assemble project), a pen (sorting bills or pictures), and a t-shirt (packing a suitcase for an overnight stay) with no external support. However, three non-full-time users had a difference of >0.5 logits among their three activities, and the findings in Study II may not necessarily be generalizable in the same extent to non-full-time users.

6.4 Reliability evidence of the ACMC (Study III)

Inconsistent scores reduce the validity evidence of the scores; therefore, it is important to evaluate the reliability of the ACMC ability measures in terms of both stability over time and rater agreements. The inter-rater agreement of version 1.0 suggested that clinical experience helps to produce consistent ratings. This is logical because clinicians need to understand how a myoelectric prosthesis works and the challenges faced by prosthesis users when controlling their prostheses. This is also the main reason why experienced raters were used to evaluate version 2.0; the aim of this evaluation was to determine whether any item or rating scale definition is well understood. The rater agreements at the item level for version 2.0 were on average higher than those of version 1.0. One reason for this could be the revised rating scale because the rating scale in version 2.0 now clearly indicates an increasing level of capacity.
The result of the test-retest ICC was excellent, and the MDC_{95} was <5% of the total ability range. The MDC_{95} is an important clinical value because the ACMC is intended to monitor the progress in prosthesis users, and the noise that is due to measurement error can mask changes that may, in fact, be attributable to the intervention. Furthermore, we know from clinical experience that the effect of prosthetic training is substantially smaller than that of hand surgery, which increases hand function considerably. To show the training effect, an instrument with a small MDC_{95} is necessary. The MDC_{95} for the same and different raters can be used as indicators to determine whether the change is due to variation or ability. However, this MDC_{95} is calculated from observations of two experienced raters, and it is likely larger in inexperienced raters.

6.5 Comparison of UL prosthetic outcome measures (Study IV)

The purpose of performing this content comparison was to show in detail what the selected UL prosthetic outcome measures are actually measuring. The comparison therefore went beyond the aims of the selected UL prosthetic outcome measures and compared their items and questions using the ICF. Five out of eight outcome measures have primary focus on function or functional status in prosthesis users but their items/questions did not link the same ICF categories. This confirms that it cannot be assumed that outcome measures that have the same primary focus will provide similar kinds of clinical data.

This comparison serves two purposes. One is to show the similarities and differences among the UL prosthetic outcome measures. The list of ICF categories shows the areas intended to be measured by the outcome measures. The purpose of UL prosthesis is to provide a mean for the users to perform their activities and participated in different activities. Therefore, it is not surprising that the items and questions were linked most of the ICF categories come under the component ‘Activity and Participation’. For example, the CAPP-FSI, PUFI, UBET and UNB cover mostly the same categories and all are under the ICF component ‘Activity and participation’. Moreover, the ACMC, OPUS and TAPES cover more than one ICF component, indicating that these outcome measures cover a wider dimension than the other outcome measures identified in this comparison. The OPUS and TAPES cover stump pain, employment, and social relationships, which are all relevant issues among upper limb amputees. The TAPES is the only outcome measure that covers ‘body image’, which is an important aspect in the acceptance and continued use of the device. However, the TAPES has items such as walking and climbing that are not so useful to evaluate UL prosthesis users.
Another purpose of this comparison is to suggest the aspects of health that are lacking in the outcome measures. Aspects such as emotional functions, psychosocial adjustment, body image and social interaction are important for both paediatric and adult prosthesis users, but only TAPES and OPUS cover these aspects. The TAPES is designed for adults and the validity of OPUS – health-related quality of life module has only been evaluated in lower limb prosthesis users. Since there is a need for such an outcome measure for paediatric users, further validation of the OPUS for paediatric upper limb prosthesis users is thus encouraged.

6.6 Methodological considerations

6.6.1 Study I, II and III
The strength of psychometric evidence should always be interpreted in the light of the methods used to search for the evidence. Three major elements may have affected the evidence in this thesis: (i) samples, (ii) data collection procedures, and (iii) methods of data analysis.

Samples
The ACMC has been examined across individuals with ULRD or AA, a wide age range, different sexes, different prosthetic sides, varying prosthetic experiences, and different wearing times. This is necessary because it covers the range of prosthesis users at which the ACMC aims. The use of samples from both individuals with ULRD and individuals with AA is common among the validations of UL prosthetic outcome measures. This is probably because these two groups often attend the same clinic, and the procedure of prosthesis fabrication is somewhat similar. One main limitation of the samples in all three studies was that the participants were all self-selected. However, the proportion of males/females in the samples represents the populations of ULRD and AA in that more males than females have limb deficiencies or amputation. There were more left-sided than right-sided prosthesis users in the samples because of the high number of ULRD in the samples and because left below-elbow deficiency is the most common type of ULRD fitted with UL prostheses.

In Study I, there were more pediatric than adult prosthesis users because children change their prostheses more often than do adults and therefore attended the LDAPC more often than did adults during the data collection period. The wide ability range of the sample in Study I is a strength, and the mean ability range was close to the mean item difficulty. This suggests that the sample in Study I was suitable for validation of the ACMC.
In Study II, the sample was strategically recruited to meet the aim of the study. Different types of prosthesis users, such as those with different prosthetic levels and prosthetic experiences, were recruited to examine the influence of activity on their ability measures. The use of ‘minimization’ sampling to assign prosthesis users to different activities was a strength of Study II. This was necessary to perform a fair comparison of the influence of activities on groups with similar characteristics. However, there was a relatively small number of less-capable users in the sample.

In Study III, the sample was also strategically recruited to meet the aim of the study. Prosthesis users with stable abilities were recruited so that errors from the ACMC itself or from the measurement procedure could be estimated. Therefore, the sample included a large number of users with more than 5 years of experience because they usually have a more stable ability than less experienced or new users. It was not easy to recruit participants that could take part in the retest session, and the recruitment therefore took quite some time. An even number of full-time and non-full-time users is a strength of the sample because it allowed us to see their variations between test-retest sessions.

The sample size fulfilled the requirement of stable calibration for Rasch analyses (Studies I and II)\textsuperscript{184, 185} and test-retest reliability (Study III).\textsuperscript{186} However, the size of the subgroups for DIF analysis (Study I) was too small to draw a definite conclusion regarding whether DIF was present in the items. Similarly, each activity had only been performed by 30 prosthesis users in Study II; therefore, the findings must be confirmed with a larger sample.

**Data collection procedures**

It was a conscious decision to include raters with different experiences to collect the data in Study I. This was because we aimed to determine how the ACMC worked with raters from no experience to those with many years of experience. Study I raters have various experiences and two of them were OT students; therefore, variation in the data was expected to be larger than in studies using only experienced raters. Rater influence on data is a known influential factor in clinical observational measures. Often, variation among the data is probably due to inexperienced raters. However, because the data were collected in a typical clinical setting by raters with different experiences, the validity evidence in Study I supported the use of the ACMC in a typical clinical setting.
However, in some cases, the use of multiple raters may not be suitable for the aim of the evaluation, such as the evaluation of the influence of activity on the ACMC ability measures. Sometimes, it is preferable that the same rater assesses the individuals to minimize unwanted variability in the ratings,\(^ {187}\) as was the case in Study II. It was a challenge to evaluate 180 assessments, and any error would have affected the results. However, based on the intrarater reliability in Study III, it could be assumed that this consistency also existed in Study II. In addition, among all 180 assessments, 10 were the ‘test session’ assessments, which were also rated by Rater 2 in Study III. The fact that the inter-rater agreement of the test session was good indicated that ACMC version 2.0 was used well to rate the participants.

The assessments were collected from either live (Study I) or video-recorded (Studies II and III) settings. The ACMC is always assessed in a live setting, and it was therefore important to validate its use in a live situation. Video recording was used in Studies II and III, and the advantage of using videos was that we were able to look at the performances repeatedly. However, as also described in the UBET study,\(^ {168}\) sometimes the intact hand blocked the view of the prosthetic hand, which made it difficult to assess the use of the prosthetic hand. In the ACMC assessments, because the users walked around during the activities, it was not always clearly shown in the video whether the participants needed visual feedback or not. This made it difficult to score the items on ‘the need for visual feedback’ in Studies II and III when collecting ACMC assessments. From clinical experience, we know that it is always easier to assess visual feedback items in live assessments.

**Methods of data analysis**

The Rasch measurement approach was mainly used to search for evidence in Studies I and II. Apart from the above-mentioned advantages of Rasch analysis, another advantage of Rasch analysis in Study I was its ability to handle missing data, because logit measures are not a sum of raw scores, but an estimate of odds. However, one limitation of the Study I analysis was that the impact of raters was not taken into consideration. The Rasch RSM allows only the analysis of items and persons, whereas the MFRM allows the analysis of items, persons, and raters. The item difficulties and participant abilities likely would not have changed if the MFRM model had been used, but the MFRM allows for the analysis of rater severity and possible rater error.

One debatable issue is the MnSq range (0.5–1.5) chosen to interpret item fit in Study I. This range is wider than the MnSq range of 0.6–1.4 in the first validation of the ACMC.\(^ 4\) An MnSq range of 0.5–1.7 has been recommended
for clinical observational data,\textsuperscript{103} and the following question has also arisen: ‘What kind of data variation do we expect?’ If clinical observational data are collected by experienced raters only, then a smaller variation in the data would be expected compared with data collected by raters with mixed experience. Study I data were collected by raters with 0 to 20 years of experience; therefore, a larger variation was expected than that of the data collected by only experienced raters. It thus seemed logical to use a range of 0.5–1.5 to interpret item fit in Study I. In future studies of the ACMC involving raters that have gained an adequate level of consistency, a narrower MnSq range may be employed to interpret item fit.

In Study III, the ICC was chosen as the reliability coefficient because it can be compared with other outcome measures in the prosthetic field. However, it is widely known that the ICC is sensitive to within-subject variance.\textsuperscript{188} Therefore, the Bland-Altman method was also used to examine the test-retest agreement because it is not affected by variance within a group.\textsuperscript{189, 190} The weighted $\kappa$ was chosen to analyze agreements at the item level because we aimed to compare the weighted $\kappa$ results with the previous rater agreement study of the ACMC, although the ICC is equivalent to the weighted $\kappa$.\textsuperscript{191}

6.6.2 Study IV

This content comparison was specifically focused on UL prosthetics. Therefore, outcome measures for musculoskeletal injuries in UL amputees were not included for comparison, although these measures are very useful in measuring physical body function in amputees and persons with ULRD. The selection was also narrowed to include only the outcome measures that used UL prosthesis users as subjects in their psychometric evaluations; therefore, fewer instruments were present in this study than in the two reviews published around the same time.\textsuperscript{82, 83} One advantage of a more strict selection of outcome measures is that it is easier for clinicians to compare the outcome measures and to judge whether the outcome measures are able to provide information in line with the aims of their evaluations in clinical practice.

Compared with the other three ICF components, the ‘Environmental Factors’ categories are very general. This has also been pointed out by researchers in assistive technology.\textsuperscript{192, 193} Assistive devices, such as P & O devices, are included in one category ‘Assistive products and technology for personal use in daily living.’ If we had linked the items only to this category, then it would not have been possible to see their similarities and differences. Therefore, a decision was made to link the items according to their intended use in human functioning; for example, grasping using a prosthetic hand was linked to
grasping using a human hand. This way of viewing assistive devices according to their intended use has also been supported by assistive device researchers.\textsuperscript{193} The linking process was conducted according to the linking rules suggested by the ICF and Dr. Cieza.\textsuperscript{9, 157, 158} The communication with Dr. Cieza was also extremely valuable in applying the linking rules.

6.7 Further research on the ACMC

Future research on the ACMC should continue to search for psychometric evidence for version 2.0. The Standards suggest a new process with which to gather evidence if the test has a new version.\textsuperscript{105} Evidence on the technical qualities of the 22 ACMC items must be searched, especially now that the ACMC is used by ACMC raters from different countries. In addition, evidence based on the response processes must be searched for the 22-item difficulty hierarchy, revised rating scale, and person fit statistics. One important question concerning the item difficulty hierarchy is whether it would remain unchanged for persons with ULRD and for persons with AA if a large enough sample is obtained to perform the analyses separately. Another question is whether the item difficulty hierarchy would remain unchanged if samples from different countries are used. Bond suggested that if the order of item difficulty stays the same in different samples, that would address the very essence of validity.\textsuperscript{194} Therefore, validation of the item difficulty hierarchy among different samples would provide valuable evidence for the ACMC.

One important validation concerning evidence based on response processes involves the investigation of how test users reason their scores during scoring process.\textsuperscript{105} Every ACMC rater must complete a training course, and showing whether they clearly understand the items and rating scale use is an important piece of evidence. This evidence shows the effect of rater training.\textsuperscript{116} Evidence based on internal structure should be continued in searching for the existence of DIF in ACMC items if subgroup sizes can support the analyses. Different diagnoses (ULRD and AA), sex, prosthetic side (dominant and nondominant side), and samples from different countries are several person characteristics that can potentially show DIF in the ACMC. The combination of items in version 2.0 is not likely to make the ACMC multidimensional, but if new items are going to be added to the ACMC, such as finger movements or elbow movements, then evidence for unidimensionality must be gathered again.

In terms of evidence based on relations to other variables, a possible future validation might involve evaluation of how the ACMC ability measures correlate with the UNB scores or client-rated questionnaires such as the PUFI or OPUS. Valuable evidence would be provided if the UNB test and the ACMC
are related to each other. Further validation with some widely used variables in the prosthetic field, such as the time between amputation and prosthetic fitting, amputation level, and amount of pain, would also be valuable.

In terms of the reliability aspects of the ACMC, the MDC95 value is now based on the assumption that measurement error or variation is uniform across the entire ability range. However, it seems that variation is larger in non-full-time users; therefore, it is possible that the MDC95 value would be different between new and experienced users or between full-time and non-full-time users. If it is possible to recruit large numbers of individuals within different subgroups, it would be valuable to investigate the MDC for different subgroups. A further validation would involve calculation of the ‘minimal clinical important difference’ (MCID), which is a value important in interpreting the clinical relevance of observed change. The MCID is the threshold at which a person or group has just begun to experience an important improvement; namely, when prosthesis users have just begin to experience an improvement in controlling their prostheses.

Evidence based on test consequence is a new source of evidence suggested by Messick. It concerns the possible impact of the test on both the test givers and test takers. Therefore, this evidence refers to the long-term goal of the use of a test. Although more evidence must be searched among other sources, one question concerning evidence based on the consequence of the ACMC is whether ACMC raters found it useful to evaluate their clients. This valuable evidence can be collected in the future, after the ACMC has been consistently used by raters in different prosthetic clinics.

Further research on the activity influence on the ACMC ability measures should be carried out using a large sample of non-full-time users. Furthermore, more activities are needed to investigate whether other activities would give different results.

6.8 Current status of the selected prosthetic outcome measures

The ACMC, UBET, and UNB test are currently used in different prosthetic clinics. All client-rated questionnaires with the exception of the CAPP-FSI are also being used in different clinics. After the publication of this content comparison, new validations of the OPUS and TAPES have been published. The validation of the UNB test is also underway. No further validation has yet been published for the UBET or CAPP; however, in line with other researchers in the field, further evidence and development of the UBET and CAPP are recommended.
Although psychometric evidence is important, clinicians should also be concerned with issues such as the clinical usefulness of a new instrument. One question is how clinicians can apply the work from this thesis in their clinical practice. Therefore, it is important to understand the clinical implication of the findings in this thesis.

6.9 Clinical implications

6.9.1 Clinical use of the ACMC

While the goal of prosthetic training is to help the user to integrate the prosthesis into his/her daily life, good control of the prosthesis is a prerequisite. The evidence on unidimensionality indicates that all items work together to measure the six aspects related to the capacity for myoelectric control. One implication of the evidence on unidimensionality is that the ACMC can be used as a metric with which to measure capacity. The ACMC items range from low to high difficulty, which enables the ACMC to differentiate prosthesis users of different capacities. I propose the use of the item difficulty hierarchy as a guideline for prosthetic training. For example, when a user is able to use their prosthetic hand in space, the training should proceed to other aspects.

The finding in Study II indirectly indicates what the ACMC is measuring (the ability to control a prosthesis) and is not measuring (e.g., the ability to perform an activity independently). If the aim of a clinical evaluation is to assess the ability to control a myoelectric prosthetic hand, then the ACMC is an appropriate tool. If the aim of an evaluation is to assess whether a prosthesis user can perform daily activities independently regardless of whether the prosthetic hand is being used, then other instruments that evaluate whether a user can perform an activity independently would probably be useful. However, it is widely known that unilateral users can perform many daily activities with their intact hands and their residual limbs or other body parts; therefore, the fact that prosthesis users are able to perform daily activities independently does not mean that they have good control of their prostheses.

The results of Study II suggest that six standardized activities can be used interchangeably for ACMC assessments. Again, the ability measures may vary more for non-full-time users than for full-time users. If time allows, two standardized activities can be used in one ACMC assessment because this
provides more opportunities for the rater to observe the items and rate them accurately.

The ACMC is designed to indicate changes between assessments. The MDC_{95} can serve as a guideline to indicate change. However, the results of test-retest reliability show that non-full-time users tend to demonstrate larger variation than do full-time users. This means that ACMC raters must consider the prosthetic wearing time when interpreting changes between assessments because we know that prosthesis users may decrease or increase their wearing time for various reasons, such as skin rashes or motivation. Furthermore, the MDC_{95} is calculated based on ratings from experienced raters; therefore, a new rater should give himself/herself a wider margin.

6.9.2 Selection of an appropriate outcome measure
Clinicians caring for patients with UL prosthetics often encounter individuals with various body function impairments, activity limitations, and participation restrictions. Therefore, diverse outcome measures capable of addressing different areas are needed. The content comparison provides a clear picture of similarities and differences among the measures and can be used as a guide to select an appropriate outcome measure for clinical evaluations.

The comparison highlights the use of a mixture of outcome measures to cover different aspects of health and functioning. Because of busy clinical routines, it is not always possible to use several tools during a single visit. One way to overcome this problem could be to ask the clients to fill in the questionnaire in advance (via post), and the clinicians then go through it with the clients during the visit. The clinician can then select one of the observational tool measures based on his/her evaluation aim.

Although more work on all of the prosthetic outcome measures is required, as suggested by Hubbard\textsuperscript{132} at the SSC in 2009, now is the time to try out the newly developed validated outcome measures, use them in a consistent manner, and see if they are clinically useful. The instrument developer is responsible for providing evidence for the instrument,\textsuperscript{105} but the test users (i.e., clinicians and other prosthetic professionals) are responsible for judging whether the ACMC and other outcome measures are able to produce valid and reliable measurements that help them to make clinical decisions and demonstrate the effect of prosthetic fitting.
7 Conclusion

Based on the evidence in this thesis, the ACMC can be recommended to measure the ability to control a myoelectric hand. Compared with 5 years ago, before this doctoral project, more evidence has been gathered to support the use of the ACMC to measure the ability to control a myoelectric hand. Of all evidence reported in this thesis, the strongest is the unidimensionality of the ACMC. The ACMC items have sufficient technical qualities, and the item difficulty hierarchy matches clinical experience. Reliability evidence also supports the stability of the ACMC measures. Furthermore, the use of a mixture of outcome measures is recommended to cover different aspects of health.

Syftet med denna avhandling var därför att söka psykometriska evidens för ACMC samt att jämföra de instrument som utvecklats för bedömning av handprotesanvändare. Bedömningar av personer i olika åldrar och med olika kön som använder myoelektrisk handprotes ingick i de tre första studierna. Rasch-analys och reliabilitetsstatistik användes för att analysera data och studera om i) ACMC är endimensionell, ii) om instrumentet fungerar olika för personer beroende på protessida, kön eller ålder, iii) om den 4-gradiga bedömningsskalan fungerar optimalt, iv) om protesanvändares ACMC-värde är lika oavsett vilken standardiserad aktivitet som utförs, samt för att studera v) stabilitet i upprepade mätningar. I studie IV gjordes en sökning i olika vetenskapliga databaser för att finna litteratur som beskriver instrument för bedömning av handprotes-användare. De instrument som validatorats specifikt för dessa personer valdes ut för jämförelse. Genom att länka begreppen i varje bedömningspunkt till motsvarande ICF kategori kunde de områden som instrumenten täcker kartläggas.


Konklusionen är att användning av flera instrument rekommenderas för att mäta olika aspekter av hälsa hos protesanvändare. Baserat på evidensen i den avhandling, kan ACMC rekommenderas för att mäta förmågan att styra en myoelektrisk handprotes.
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Errata

Study I
P.470, 3rd paragraph, line10: CI, should be 'confidence bands'
P.470, Fig.2. ‘confidence intervals' and CI, should be ‘confidence bands’

Study IV
P.122, Table IV – ‘Body Functions’, should be ‘Activity and Participation’
Doktorsavhandling/Doctoral thesis with focus on Nursing.

Doktorsavhandling/Doctoral thesis with focus on Nursing.

Vetenskaplig uppsats för licentiatexamen/Academic essay.

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Vetenskaplig uppsats för licentiatexamen/Academic essay.

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Vetenskaplig uppsats för licentiatexamen/Academic essay.

Doktorsavhandling/Doctoral thesis with focus on Occupational Therapy.

Vetenskaplig uppsats för licentiatexamen/Academic essay.

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* Seriens namn var tidigare (nr 1–24) ”Örebro Studies in Caring Sciences”.*


