CHAPTER 1

General Introduction

"Is it nothing to have the mind awakened to the perception of the numerous proofs of design which present themselves in the study of the Hand - to be brought to the conviction that everything in its structure is orderly and systematic, and that the most perfect mechanism, the most minute and curious apparatus, and sensibilities the most delicate and appropriate, are all combined in operation that we may move the hand?"

Sir Charles Bell
The Hand - Its Mechanism and Vital Endowments as Evincing Design *(1833)*

Introduction

Together with the brain, the hand is the most important organ for accomplishing tasks of adaptation, exploration, prehension, perception and manipulation, unique to humans.[1] To study the anatomy and kinetic chains of the hand and the complex interplay of more than 40 muscles that control its movements requires an appreciation of the biomechanics of the hand and its dexterity (Fig. 1).[2]
The muscles of the fore arm and hand can be conveniently arranged according to innervation and localisation. Usually the muscles are divided into extrinsic ones, where muscles have their origin proximal to the hand and intrinsic muscles which have their origin and insertion within the hand (Table 1). Sterling Bunnell[3] wrote that "the intrinsic muscles of the hand, though tiny, are important because, with the long extensors and long flexors, they complete the muscle balance in the hand".

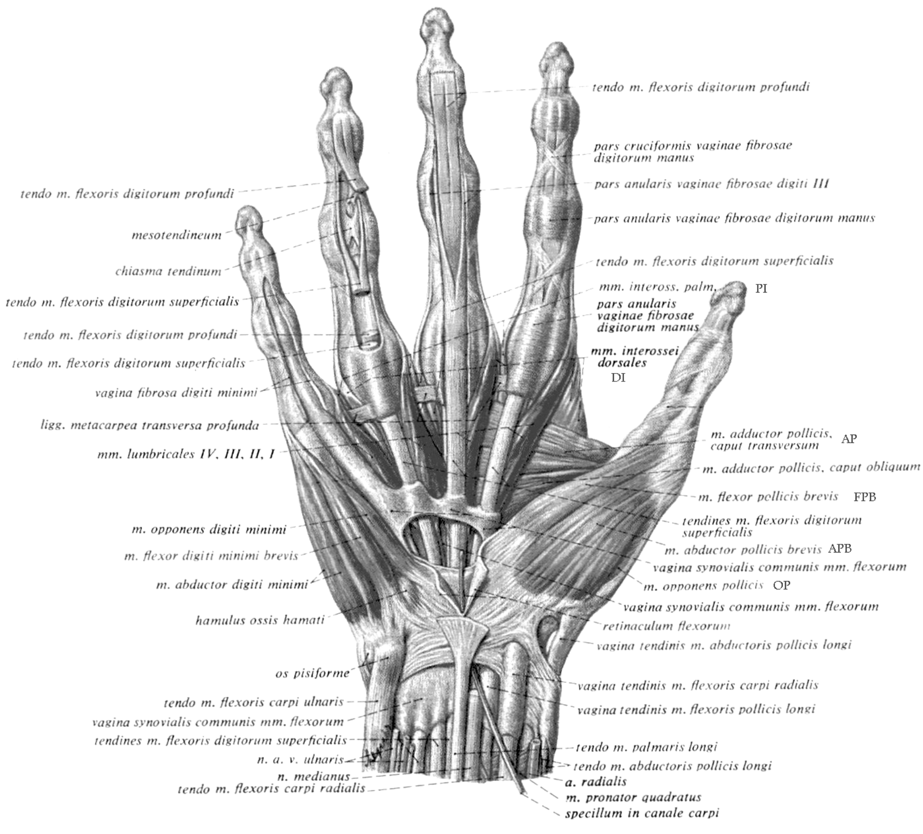

Fig. 318. Muscles of the palm after removal of the larger part of the *aponeurosis palmaris*. The tendon sheath of the middle finger was split along its entire length. The *retinaculum flexorum* was partially opened.

Figure 1; from: Sobotta atlas van de menselijke anatomie, 2e druk. Houten, Bohn Stafleu Van Loghum, 2000. R. Putz en R. Pabst (red.), (with permission)

Table 1. Extrinsic and intrinsic muscles listed by innervation.

	Extrinsic				Intrinsic	
	Elbow	**Wrist**	**Fingers**	**Thumb**	**Fingers**	**Thumb**
Ulnar		FCU flexor carpi ulnaris	FDP (dig 4,5) flexor dig. prof.		PI Palmar interossei DI Dorsal interossei Lumbricals dig. 4,5 Hypothenar muscles	AP adductor pollicis FPB (part) flexor pollicis brevis
Median	PT (pronator teres)	FCR flexor carpi radialis PL palmaris longus PQ pronator quadratus	FDP (dig 2,3) flexor dig. prof. FDS (dig 2-5) flexor dig. sup.	FPL flexor pollicis long	Lumbricals dig. 2,3	APB abd. pollicis brevis OP opponens pollicis FPB (part) flexor pollicis brevis
Radial	BR (brachio-radialis) Supinator	ECRL ext. carpi rad. Longus ECRB ext. carpi rad. Brevis ECU ext. carpi ulnaris	EDC ext. dig. communis EDQ ext. dig. quinti EIP ext. indicis prop.	APL abd. pollicis long EPB ext. pollicis brevis EPL ext. pollicis long		

The intrinsic muscles are sometimes referred to as tiny or small muscles of the hand, but this should not be interpreted as weak because some intrinsic muscles (especially the index finger DI and AP) have a cross-sectional area similar to several strong extrinsic muscles.[4] The term "tiny" or "small" is therefore correct only in that the intrinsic muscles are short.

This thesis focuses on the intrinsic muscles of the hand. Loss of intrinsic muscle strength of the fingers can cause severe loss of hand function, e.g. firmly holding a key with paralysis of intrinsic muscles of the hand can become impossible (Fig. 2).

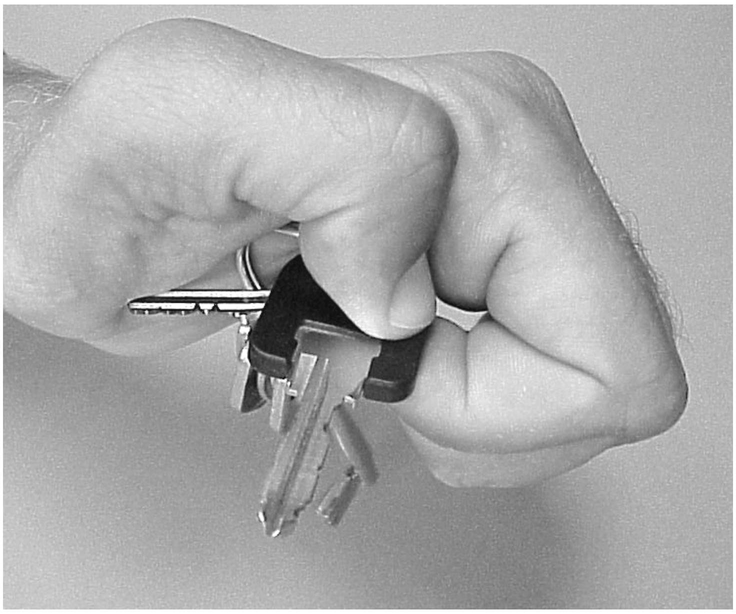

Figure 2. A patient with loss of all intrinsic muscles holding a key.

Muscle strength testing

For many centuries measuring muscle strength has been an area of interest for those who have been studying and are responsible for diagnosing many diseases that are accompanied by loss of strength.[5] Numerous neurological diseases are accompanied by atrophy of the intrinsic muscles of the hand. Therefore, muscle function strength testing is frequently used for clinical decision making in rehabilitation medicine, neurology, hand surgery and physical therapy. The purpose of this muscle strength testing is, besides diagnosis, to evaluate and compare treatments, to document progression or regression of e.g. muscle strength during rehabilitation, to provide feedback during the rehabilitation process, and to evaluate handicaps/restrictions of participation after injury.[6]

In an historical outline of manual muscle strength testing[7] (MMST), the first person to design a numerical system of grading muscle action was Lowman in 1911, followed closely by Lovett who introduced the testing grades based on gravity.[8] The British Medical Research Council (MRC) specified a similar 0 to 5 scale where complete paralysis is graded as 0, grade 3 is when the limb segment can be moved actively against gravity, and grade 5 is normal strength.[9] The procedure for MMST is simple in that no equipment is needed. The hand of the examiner is used to feel the muscle activity and to give resistance to determine which grade the muscle can be given (Fig. 3).

Figure 3. Manual muscle strength testing of the abduction strength of the little finger; the right hand of the examiner gives resistance to determine which grade the muscle can be given.

The most frequently used textbooks on MMST are still based on this early system of muscle grading, e.g. Kendall and Kendall[10] and Daniels L. Worthingham.[11] Some modification for MMST of the hand has been proposed by Brandsma et al.[12] In MMST of the hand, gravity is not taken into consideration, therefore grade 3 is considered as the ability of the muscle (group) to perform a full range of motion (ROM). When the interossei and lumbricals are tested as a group in the intrinsic plus position (MCP flexion and IP extension), grade 2 is given when the proximal interphalangeal (PIP) joint extension is less than 30° short of full extension.

Brooke modified the 0-5 scale into an 11-point scale, adding "+" and "-".[13] A 9-point scale has been investigated by Brandsma et al. for reliability in patients with neuritis due to leprosy.[14] Strength was graded on a modified MRC scale with 9 grades: 5, 4+, 4, 3+, 3, 2+, 2, 1 and 0. Overall agreement appeared to be good or very good (Kappa; 0.61-1.00). However, when data for hands with normal strength (grade 5) or complete paralysis (grade 0) were excluded from the analysis, the reliability of the remaining mid-range scale was not acceptable.

Limitations of MMST

a) Although the textbooks usually present the muscle tests as if muscles can be tested in isolation, clinicians should be aware that usually a muscle group is tested rather than just one muscle. Some have suggested labelling the movement rather than the muscle, e.g. grading the palmar abduction movement of the thumb instead of abductor pollicis brevis (APB), because several muscles are active when testing the palmar abduction of the thumb. Only a few muscles can be graded in isolation, e.g. flexor pollicis longus, flexor digitorum profundus and first dorsal interosseous (1DI).

b) The MRC uses a 6-point numeric scale (grades 0-5) and seems to indicate a constant distance between points. However, it is an ordinal scale with disproportional distances between grades; e.g. grade 4 is not twice as strong as grade 2. It might have been more appropriate to use terms such as normal, good, fair, trace and paralysed.

c) Another important comment concerning MMST was made in the American Society of Handtherapists (ASHT) recommendations,[7] that its most appropriate use is in cases of extreme muscle deterioration. MMST is not appropriate for higher-level muscle function due to lack of sensitivity and precision, and should be used in conjunction with other evaluation tools. We contend that MMST is most useful for weak muscles with grades of 1, 2 and 3, but not for the higher grades.

d) MMST is dependent on the examiner’s ability to assess the pressure as a parameter for strength. Experience of the examiner is important for reliable measurements.

History of dynamometers for the hand

One of the first dynamometers for measuring hand strength was the Graham-Desaguliers dynamometer, which was developed in London in 1763. The Regnier dynamometer was invented in Paris in 1798 to measure the traction properties of artillery horses, but was designed as an all-purpose instrument to measure specific human muscle groups as well.[8]

In the past decades many different dynamometers have been introduced, e.g. cable tensiometers, sphygmomanometers, vigorimeters,[15] isokinetic dynamometers and strain gauge dynamometers.

In response to the confusion generated by the many commercial and experimental grip strength instruments, the California Medical Association in 1956 evaluated the most commonly used instruments.[16] They found the Jamar, first introduced by Bechtol in 1954,[17] to be the most accurate. In 1978 the American Society for Surgery of the Hand recommended that the second position of the Jamar should be used and in 1981 the ASHT made additional recommendations, e.g. concerning posture and verbal instructions during measurements.[7] Grip strength measurements with a dynamometer have become popular and have been studied extensively. Less studies have been conducted to investigate pinch strength measurements.

Van der Ploeg et al.[18] noticed the shortcoming of the MMST method by giving an example of strength measurements of the biceps muscle as an elbow flexor. The biceps needed 5 N of its normal strength (250 N) to overcome gravity; thus grade 3 corresponds with only 2% of the full strength of the biceps muscle.

Dynamometers for intrinsic muscle strength measurements

In his thesis van der Ploeg noted that most dynamometers have a scale far too crude for measuring forces in very small muscles like the abductor digiti quinti. However, assessing the strength of these muscles is of great importance in clinical neurology in the evaluation of mono- and poly-neuropathies. He noted that there is a need for an accurate device for these muscles.[19]

One of the first to develop a dynamometer for the intrinsic muscle strength was Mannerfelt, who later manufactured a new device called the *Intrins-o-meter.*[20] In 1997 he reported a study in 48 patients with ulnar nerve compression.[21] Rosen et al. noted that assessing muscle function using the *Intrinsi-o-meter* was difficult due to the extremely small forces, and the instrument was difficult to handle and read. They suggested using MMST and grip strength measurements to evaluate nerve function. Interestingly they found a poor recovery of the intrinsic muscle strength with the Mannerfelt instrument and good grip strength recovery.[22 23]

Several others have developed instruments mainly to assess the abduction of the thumb.[24-26] Some needed a specially constructed jig, e.g. to measure wrist, finger (metacarpo-phalangeal joints) and thumb extension strength.[27]

Rotterdam Intrinsic Hand Myometer (RIHM)

In 1995 inventories were made at our department to establish which clinical evaluation instruments were available to assess the outcome after peripheral nerve surgery. Three methods were often used to assess the recovery of muscle strength: MMST and grip and pinch strength dynamometers.

Having encountered several patients with good grip strength but poor recovery of the intrinsic muscles strength, we questioned whether grip strength measurements were appropriate. We acknowledged the need for a dynamometer to measure the intrinsic muscles in isolation. Such a dynamometer should be easy to handle, e.g. portable and with an ergonomical design. It should also have the possibility to measure the opposition force of the thumb. Reliability should be good with acceptable measurement error making it possible to detect reasonably small changes in muscle strength.

In this thesis we present the development of a new dynamometer for intrinsic muscles, the validation in patients, and its application in patients with nerve injury.

Outline of this thesis

Chapter 2 Describes the functional anatomy of the intrinsic muscles of the hand and the pathology. Possibilities to assess muscle strength (manual and instrumental) and the various therapeutic options (prevention of complications, exercises for strengthening) are discussed.[28]

Chapter 3 The first dynamometer which was utilised was a generic strain gauge instrument, the AIKOH. Several intrinsic muscle actions were measured for reliability.[29] The calculated Standard Error of Measurements (SEM) and the Smallest Detectable Differences (SDD) for intraobserver and interobserver values indicated that only relatively large changes in strength could be confidently detected with this technique.

Chapter 4 Presents the strength measurements of the lumbrical muscles of the index and middle finger in a group of patients with ulnar nerve injuries.[30] The contribution of the interosseous muscles in maintaining the intrinsic position compared to the lumbrical muscles was measured. The MRC scale (0-5) was also compared to the dynamometry measurements.

Chapter 5 To gain better insight into the measurement error in strength measurements of the hand in general, we studied the measurement error for intraexaminer and interexaminer measurements of the grip and pinch measurements in a consecutive sample of 33 patients with hand injuries. The measurement error was compared between measurements of the injured and noninjured hands, and between experienced and inexperienced examiners.[31] Literature was studied concerning other reliability studies of grip and pinch force measurements. A method to judge and compare SDDs was explored.

Chapter 6 A dynamometer was designed and fabricated with specific requirements: i.e. improved reliability to measure the muscle force of the intrinsic muscles, hand-held and portable, possibility to measure the opposition force of the thumb (Opponens Pollicis muscle), ergonomically designed handgrip, appropriate visual feedback of line of pull, and minimal errors from off-axis loading thus allowing measurement of axial forces only.[32] This chapter describes the technical aspects of the dynamometer design, which was named the Rotterdam Intrinsic Hand Myometer (RIHM).

Chapter 7 To compare the old and new dynamometers a study was undertaken to assess the accuracy of the previously used industrial dynamometer (AIKOH) and the new RIHM in applying the dynamometer perpendicularly in both planes at the digit. The angle and place of application was determined with a three-dimensional videorecording technique. Differences between the two instruments, as well as measurement error and variance between two sessions were calculated and compared. The consistency of positioning the instruments at the same point of the finger was also analysed.[33]

Chapter 8 The reliability of the RIHM was determined in 27 patients with ulnar and/or median nerve injury.[34] For the two ulnar and two median nerve innervated movements the ICCs, SEMs and SDDs were calculated and compared to the AIKOH dynamometer.

Chapter 9 Outcome of muscle strength is presented in 34 patients with ulnar and median nerve injury. The outcome of muscle strength with four methods (MMST, grip and pinch strength measurements and the RIHM) was compared.[35] Correlations between the four measurement methods were calculated.

Chapter 10 Discussion: some issues related to measurements of the muscle strength of the hand are discussed in a more comprehensive perspective, together with some limitations of the work presented here.

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CHAPTER 2

The Intrinsic Muscles of the Hand:

Function, Assessment and Therapy principles

The hand is an emblem of strength, skill, sexuality, and sensibility.
When it is damaged, it becomes a symbol of vulnerability of the whole person

Paul W. Brand (1914-2003)

Introduction

There have been many valuable studies concerning the anatomy[1-3], mechanics,[4-6] and architectural design,[7] of the intrinsic muscles of the hand. Understanding the mechanics of human dexterity requires an appreciation of the kinetic chains that comprise the hand, and the intricate interplay of muscles and ligaments that control its movements.[6] In these chains, the intrinsic muscles of the hand (Fig. 1) are of paramount importance for efficient hand function.[7]

There is a considerable decrease in functional efficiency in hands with loss of the intrinsic muscles function, often referred to as the clawhand or intrinsic minus hand (Fig. 1).[8-10]

Figure 1. Longstanding paralyses of all intrinsic muscles can cause severe clawing of the fingers.

In Table 1 the intrinsic muscles of the hand are ordered according to localisation and innervation.

Table 1. Intrinsic muscles listed by innervation.

	Fingers	**Thumb**
Ulnar innervated	Palmar interossei (PI)	Adductor pollicis (AP)

	Dorsal interossei (DI) Lumbricals dig 4,5 Hypothenar	Flexor pollicis brevis (FPB) part
Median innervated	Lumbricals dig 2,3	Abductor pollicis brevis (APB) Opponens pollicis (OP) Flexor pollicis brevis (FPB) part

A comprehensive analysis of hand function should include assessment of the strength and length of the intrinsic muscles. This will provide important information and assist the assessor in e.g. determining nerve function, deciding which muscles need to be strengthened, what splint is needed, what surgery needs to be considered (tendon transfer), etc.

Although assessment of muscle strength and length are important elements of hand function other functions, e.g. mobility, sensibility and central properties of the brain, are equally or more important for hand function. The latter controls e.g. tonus, co-ordination and speed of hand movements.

Hand tests to assess the ability of the patient to perform certain tasks have been developed by e.g. Moberg,[11] Bendz,[12] Sollerman et al,[13] and Light et al.[14] Most of such tests record how long it takes to finish a particular task. Clinicians often see that patients with impairments of the hand have quickly learned compensatory mechanisms to compensate for the lost functions. Therefore, tests at this activity or skills level may only assess the ability of the patient to compensate for lost function.

While there is little consensus about classifications of prehensile patterns of hand function[15-18], the general characteristic remains largely consistent with the following categories: three pinch grips (tip pinch, lateral or key pinch, and tripod or chuck pinch) and three modes of gripping: (power grip, spherical or flexion grip, and extension grip in intrinsic plus position).[14] It is estimated that for a full range of natural common grips, a spherical grip is required for 10%, a tripod grip for 10%, a power grip for 25%, a lateral grip for 20%, a tip grip for 20%, and an extension grip for 10% of tasks of activities of daily living. Without intrinsic muscles a power grip is somewhat weaker but still possible, but for all other grips the intrinsic muscles play an important role.

Long-term loss of intrinsic muscle function may result in irreversible joint contractures. An appropriate therapy plan (e.g. which exercises are needed, what splint may enhance hand function and prevent contractures) is needed.

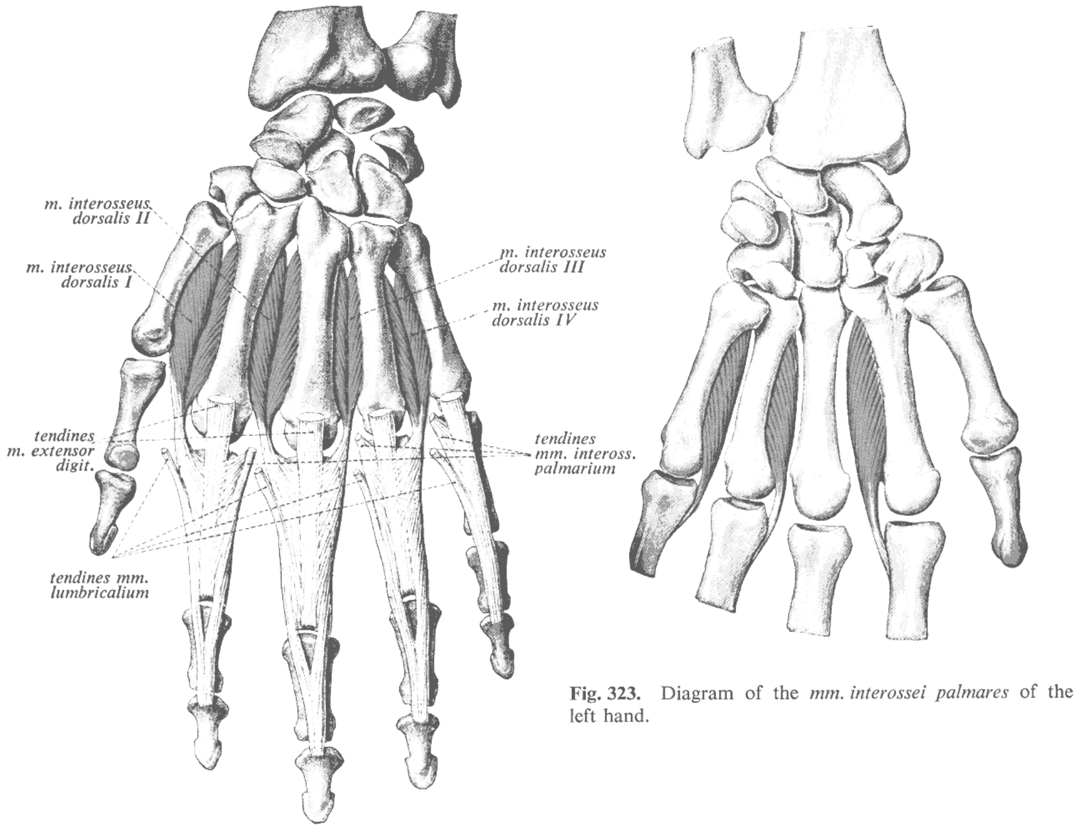
The aim of this paper is fourfold:

1. to review the functional anatomy of the intrinsic muscles of the hand.
2. to discuss the pathokinesiology of the hand with intrinsic muscle paralysis, and its consequences for Activities for Daily Living (ADL)/dexterity and muscle shortening.
3. to present possibilities for the assessment of muscle strength (manual and instrumental).
4. to discuss therapy principles (prevention of complications, exercises for strengthening).

All intrinsic muscles will be discussed separately, except for the hypothenar muscles which are discussed as a group.

1. Intrinsic muscles of the fingers

In general, every finger has six muscles controlling all the movements of the fingers: three extrinsic tendons (two long flexors and one long extensor) and three intrinsic muscles (dorsal and



palmar interosseous and lumbrical muscles). (Fig 2)

Figure 2 from R. Putz en R. Pabst (red.), Sobotta atlas van de menselijke anatomie, 2e druk. Houten, Bohn Stafleu Van Loghum, 2000 (with permission)

1.1. Dorsal and palmar interossei

1.1.1 Functional anatomy

Literature usually describes four dorsal (DI) and three palmar (PI) interosseous muscles. Stack et al.[19] suggested that it might be more correct to divide the interossei into the proximal and distal, as it is their insertion rather than origin, which dictates their action. Most dorsal interossei muscles have a more proximal attachment while the palmar interossei have a more distal attachment similar to the lumbricals.[19] According to Zancolli[20] there are three types of insertions of the interossei:

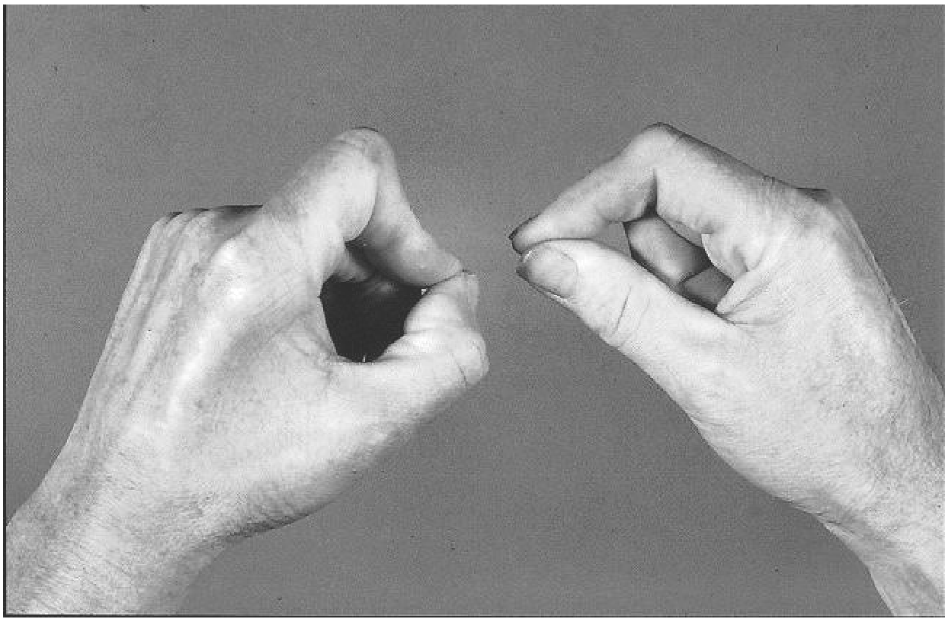
Type I	most proximal, attached to: *a.* tubercle of proximal phalanx, *b.* transverse and oblique fibers of extensor apparatus *c.* the volar plate.
Type II	is like type 1 except that there is no attachment to the bone (*a.*) And part of the insertion is into: *d.* the lateral band
Type III	has all four attachments *a, b, c* and *d.*

The first dorsal interosseous (1 DI) insertion is of type I, all other DI are of type III. All PI have the type II insertion, but variations are possible.[1 3] Because of this insertion the strongest activity of the 1 DI is in key pinch when the thumb is pressed against the mid-phalanx of the index finger. The 1 DI is also active in tip pinch, when the tip of the thumb is pressed against the tip of the index finger, but then the main action is as a flexor at the metacarpo-phalangeal (MCP) joint. The first palmar interosseous (1 PI) muscle is more active in tip pinch activities.

In Type II, the insertion into the lateral band of the extensor apparatus (*d.*) is responsible for an important extension force at the proximal interphalangeal (PIP) joints. The first palmar interosseous also produces some supination of the index finger to get good approximation of the pulps. In this respect we might consider the 1 PI as an "opponens indices" muscle in tip pinch activities.

Without interossei the finger is unstable and will collapse into the "claw" (i.e. intrinsic minus) position of flexed IP joints and (hyper-) extension of the MCP joint: therefore the interosseous are sometimes referred to as the "anti-claw" muscles.[9] The primary function of the interossei is MCP flexion/stabilisation with extension of the interphalangeal (IP) joints. This is especially evident during pinch in which the collapse of the index PIP joint is apparent in, often > 90°, flexion. This is a sign of interosseous muscle weakness and sometimes referred to as the Mannerfelt sign.[21] (Fig. 3).

Fgure 3. Mannerfelt and Froment sign on left hand of patient with ulnar nerve paralysis.



Recording the moments of the intrinsic muscles that were generated after electrical stimulation Lauer et al.[22] found that the dorsal interossei muscles were strong abductors of the fingers and generated a significant moment in MCP joint flexion and IP joint extension. Similarly, Ketchum et al.[8] found that the interossei muscles of the index finger contribute 73% to the overall moment for flexion of the MCP joint.[8] Li et al.[23] investigated the role of the intrinsic finger flexor muscles during finger flexion tasks. When an external force is applied proximally to the PIP joint, the extensor mechanism (intrinsic muscle group) is the largest component (70%) on force production of all flexors. Thus the interossei muscles are important flexors of the MCP joint together with the long flexors: flexor digitorum profundus (FDP) and flexor digitorum superficiales (FDS). However, at the PIP joint level the long flexors, primarily the FDS, and the interossei are antagonists.

When the PIP joint is flexed, some reduction of the extension moment of the interossei takes place, due to the volar displacement of the lateral bands (of about 4-mm) at the PIP joint level. At full flexion of both the PIP and distal interphalangeal (DIP) joints, the lateral bands approach the flexion-extension axis of the PIP joint, thereby minimising the extensor moment.[6]
The action of the interossei muscles can be studied separately from the extensor digitorum communis (EDC) muscles in patients with a radial nerve paralysis. If the patient is asked to extend the fingers, no extension of the MCP will occur, but the finger IP joints will extend because of the ulnar and median nerve innervated interosseous and lumbrical muscles. However, in some patients the fingers, especially the index, can be extended in the MCP joint to some degree, especially with the wrist flexed; this is probably because the angle of attachment of the dorsal interossei muscles is only 0°-5°. When the tension on the extensor tendon is increased due to the flexed wrist, this angle will go beyond the 0° and thus the interosseous muscle becomes an extensor of the MCP joint. The angle of approach to the extensor mechanism for the palmar interossei muscles is 20°-25° and for the lumbrical muscles 35°.[1]

The index finger is deprived of all long flexors and the lumbrical muscles in patients with a high median nerve paralysis. The only active muscles are the long extensors and the two interossei. In an attempt to flex the fingers the index finger will remain extended, and is accurately described as the “pointing finger” where the IP joints are fully extended and the MCP joint flexed. In high median nerve paralysis the long finger is also deprived of the long flexor, but will usually flex in grip. This is due to the attachments between the FDP tendons of the long finger and the ring finger and is called the Quadriga phenomena.[24 25] This term suggests a symmetrical organisation of the four tendons; however, the connections between the FDP of the index and middle finger are usually absent, and a strong connection between the flexor pollicis longus (FPL) and the FDP of the index finger can exist.

1.1.2 Pathokinesiology (paralyses, consequences for prehension/ADL, shortening)

The deficiency mentioned in textbooks due to loss of interossei is usually that of controlled abduction and adduction of the fingers. The loss of this action is important for those who play musical instruments or operate keyboards, but in most patients this is not recognised as a severe deficit. The loss of the interossei function of MCP flexion and PIP extension is a much more significant loss. In acute paralysis of the interossei muscles it will sometimes only be visible as a mild hyperextension at the MCP joints and slight flexed position of the PIP joints when the patient is asked to extend the fingers. However, this deformity usually progresses depending on the natural joint laxity of the hands, i.e. long, thin and hypermobile fingers will develop a so-called claw hand much quicker than thick, stiff fingers. In the mobile hands the volar ligamentous structures stretch more easily, causing increased hyperextension and subsequently less PIP extension. Extension of the PIP joints is only possible by contraction of the EDC when the MCPs are 'blocked', either actively (internally) through muscle contraction or passively (externally) through the examiners hand or a splint, preventing hyperextension of the MCP joints. In the latter situation this is called assisted extension, which is also used as a test to assess the integrity of the extensor apparatus.

Other factors that may contribute to the development of a claw hand are: hand dominance, continued use of the hand (or the lack of), compliance of the patient to perform the routine exercises to prevent joint stiffness, and use of (night) splints.

Without interosseous muscles the hand can still make a full fist, but the pattern of movement is changed (the MCP flexion takes place later than usual). The contribution of the interossei muscles in grip strength measurements will be discussed later.

In patients with a “high” ulnar lesion, the FDP muscles of the 4th and 5th fingers are paralysed and less clawing is often visible because the flexion moment at the PIP joints is decreased compared to a "low" ulnar palsy. We might conclude from this observation that clawing is also the result of visco-elastic tension of FDP. When the ulnar nerve recovers, the 4th and 5th finger will show an increasing clawing. Maintaining the length of the FDPs, i.e. preventing flexor tightness, therefore also helps to prevent clawing.

Another sign of interossei muscle weakness was first described by Andre-Thomas in 1917 and is called the Thomas sign.[26 (p. 518)] (Fig. 4). This is the tendency (compensation) of a patient with weak interossei muscles of the fingers to automatically flex the wrist in an attempt to gain a better opening of the hand, i.e. MCP extension, by means of increasing the pull on the EDC. This in fact increases the hyperextension of the MCP joints and adds to the progress of the development of the claw hand. This "trick" movement is adopted very quickly and even when the interossei have regained their strength, will often take a long time to "un-learn".

Figure 3. Thomas sign: compensation movement when interossei muscles are weak; flexion of the wrist in an attempt to gain a better opening of the hand, i.e. by means of increasing the pull on the EDC.

In longstanding paralyses of the interossei, e.g. when the ulnar nerve could not be repaired or did not recover, the PIP joints are continuously in a flexed position. This will cause a gradual stretching of the dorsal expansion (sometimes called the tri-angular ligament) over the PIP joint, which secures the lateral bands of the extensor tendon in their dorsal position. In the normal finger, the lateral bands shift dorsally and towards the central position of the finger when the PIP joint is extended. Whereas when flexing the PIP joint the dorsal expansion needs to allow the lateral bands to move volarly towards the flexion-extension axis of movement. When this dorsal expansion is elongated, the lateral bands are too much volarly, resulting in a loss of PIP joint extension. Consequently, the oblique retinacular ligament (ORL) or Landsmeers ligament is slack most of the time and will adjust to this new situation by shortening and this may result in hyperextension of the DIP joint. This is a similar progression of changes as in an extensor tendon central slip injury, causing a Boutonnière deformity.[27]

Another impairment in longstanding paralyses of the interossei muscles is related to hyperextension of the MCP joint. This causes an upward pull of the EDC tendons (bow stringing), stretching the sagittal bands. The laxity of the sagittal bands will result in an inability to maintain the EDC tendon on top of the MCP joint. The drop of the luxating tendon into the groove between the MCPs is especially observable when flexing the MCP joint. This is sometimes called "guttering" because the tendon drops into the "gutter" between the MCP joints.

The longstanding flexed position of the IP joints will result in a physiological shortening of the long flexors. This flexor tightness will increase the PIP flexion position and can cause a deterioration of the PIP flexion contractures. This is an additional argument to maintain the length of the extrinsic flexors in patients with intrinsic muscle weakness.

Shortening of the interossei muscles is called intrinsic tightness (IT), which can be caused by a trauma of the hand which can precipitate a cascade of events. The interossei are situated in rather tight compartments, therefore oedema/swelling will cause an increase of pressure in these compartments. As a result blood circulation will be hampered causing anoxia and muscle fiber death, which results in fibrosis of the muscle and shortening. This is identical to the process which causes Volkmann's ischemic contracture in the forearm.[28]

The IT test consists of two parts. First, passive PIP flexion is tested with the MCP joint extended and, secondly, passive PIP flexion is tested again but now with the MCP joint flexed. If there is a large difference in PIP flexion between the two MCP positions, intrinsic tightness is present. The long-term complications of IT can result in decreased MCP extension and a swan neck finger, i.e. hyperextension of the PIP joint. A longstanding swan neck deformity might result in a painful snapping of the lateral bands at PIP level when the finger is flexed.

In rheumatoid arthritis a different process can also lead to IT. The role of the intrinsic muscles in producing MCP subluxation in the rheumatoid hand has been documented.[29 30]

Another intricacy sometimes observed is what we call *interosseous plus*, which is a paradoxal extension: the harder the patient tries to bend the finger, the more the finger will extend in the PIP joint. This phenomena is sometimes seen in patients in which the interossei have been the only flexor of the finger for some time e.g. in high median nerve palsy, or in case of adhered flexor tendons. Although the flexors are active and can bend the finger, when a stronger grip is required the finger will extend.

The explanation is that in a non-resistant grip of a normal functioning hand there is only minor activity of the interossei muscles. However, in a strong grip, the stronger the flexors are pulling, the more the intrinsic muscles become active to stabilise the PIP joints and prevent luxation. If the long flexor is weak or poorly activated, the interossei will overpower the flexor causing PIP extension. This paradoxal extension appears to be similar to the lumbrical plus phenomena (see lumbricals) and might be called *interosseous plus.* The patient has to be taught to, gently, contract the long flexors without the action of the interossei muscles.

1.1.3 Assessment possibilities (manual and instrumental)

Although the interosseous muscles have short fiber length, some are strong and have physiological cross-sectional areas comparable to the FDS muscles.[27] In standard textbooks on muscle testing, the tests suggested are usually: abduction for dorsal and adduction for palmar interossei muscles.[31 32] These tests are useful for isolated (specific) testing of the interossei. For example, patients with an ulnar nerve paralysis can not move their middle finger sideways, which has been called the Egawa sign.[26] Functionally, it is much more meaningful to test the interossei muscles in the intrinsic plus position, by giving resistance to flexion of the MCP joints and extension of the PIP joint.[33 34] (Fig. 5).

Figure 5. Testing the strength of the intrinsic muscles in the fingers.

Some have suggested that dynamometry of the interossei muscles is possible, indirectly, by measuring the grip strength of the hand with e.g. a Jamar dynamometer. Janda et al. advocated to use the smallest handle position of the Jamar because the intrinsic muscles were most active in that position.[35] Kozin et al.[10] tested 21 healthy persons who underwent median and ulnar nerve blocks at the wrist level; the average decrease in grip strength was 38% after ulnar nerve block.

Pinch data in the study by Kozin et al. revealed a significant decrease in key pinch of 77% after ulnar block and 60% after median block.[10] For evaluating and monitoring the motor function of the ulnar nerve, pinch strength measurements seem more meaningful than grip strength measurements.

Specific measurements of the first dorsal interosseous muscle can be done with dynamometers such as the RIHM,[36] the Intrins-o-meter of Mannerfelt,[37] or the Preston pinch gauge device.[38]

1.1.4 Therapy principles (prevention complications, strengthening, ADL)

Prevention of contractures is directed at the PIP joints. A (night) splint with the MCP joints in flexion and IPs in extension is advisable. These splints can help to prevent PIP flexion contractures and are especially important in longstanding problems. Increased hyperextension of the MCP joints, due to stretching of the volar plate, is also prevented in this position.

During the day the so-called "knuckle-bender" can assist the patient in some ADL functions. This splint will also help to move the PIP joint into full extension during the day and will maintain the integrity of the extensor mechanism. When patients choose not to wear a splint, they need to be taught how to do assisted extension exercises by blocking the MCP joints with their hands and routinely massaging to extend the IP joints (Fig. 6).

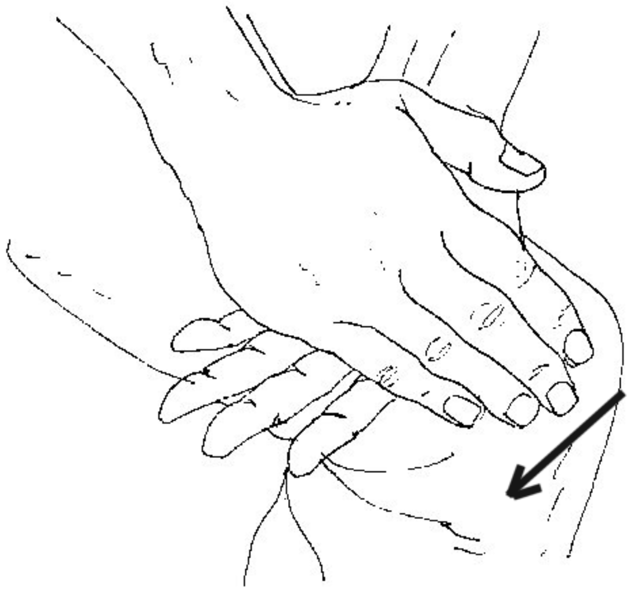


Figure 6. Prevention of IP flexion contractures by massaging the fingers.

Exercises to strengthen the interossei muscles are all aimed at movements which flex the MCP and extend the IP joints. Therefore, exercises for the interossei muscles are all activities in intrinsic plus position: e.g. grasping a book, plate or a cylindrical object like a large bottle. Specific training of the first dorsal and palmar interossei are activities for which key and tip pinch activities are required.

To correct the long flexor tightness, the patient is taught to stretch the flexors by holding the hand flat on e.g. a table and by moving the forearm towards an angle perpendicular to the table. In a similar fashion, the hand can be placed on the seat of the chair while the patient sits on the hand and pulls the forearm towards the body. A night splint with the fingers and hand in extension might be necessary in severe cases.

1.2 Lumbricals

1.2.1 Functional anatomy

The lumbrical muscles are unique muscles in several aspects. They connect two extrinsic antagonistic muscles. Proximally the lumbricals are attached to the FDP and distally they are inserted into the lateral band of the extensor tendon. The third and fourth lumbricals also connect, by their bi-penal origin, two adjacent FDP tendons.

The function of the lumbrical muscles is much debated and some even considered these muscles to be redundant. Brand suggested that the lumbrical muscles are not relevant for MCP flexion. He explained this with an illustration of a father carrying a child; it does not matter what the child (i.e. lumbrical) is carrying, the father (i.e. FDP) has to carry it anyway.[27] Therefore, the lumbrical muscles have a unique ability to contract without adding flexion torque at the MCP joint, in contrast with the interosseous muscles which, when extending the IPs, need a stronger contraction of the EDC to counteract the flexion moment at the MCP joint level. The lumbricals provide a more efficient source for IP extension than the interossei. Any contraction of the lumbrical muscle for IP extension simultaneously, reduces the visco-elastic force of the FDP tending to flex the IP joints. Accordingly the lumbrical can be regarded as a *deflexor* of the PIP joint.[39] Its direct contribution to MCP flexion is small and in the flexed finger may be non-existent, but its *indirect* contribution to IP joint extension by decreasing the flexion torque is quite substantial.[40]

With the smallest physiological cross-sectional area, it is certainly not a strong muscle. The lumbricals have a very long fiber length (40-48 mm) which indicates that they are designed for long excursions. If the lumbrical fiber length was short, FDP excursion could stretch the lumbrical sarcomeres to a point that they were unable to generate active force.[7]

The lumbrical muscles are richly endowed with muscle spindles, their passive stretch by contraction of the FDP might both inhibit finger extensors and facilitate wrist extensors.[40-43] For this reason the lumbrical muscles have been called “tensiometers” between long flexors and extensors.[44] Leijnse and Kalker[25] concluded that the lumbricals are in an optimal position for proprioceptic feedback concerning the PIP-DIP joint mechanism.

These unique properties of the lumbricals indicate that they are probably important in fast, alternating movements, e.g. in typing and playing musical instruments.[45]

1.2.2 Pathokinesiology (paralyses, consequences for prehension/ADL, shortening)

In low median nerve injuries the lumbrical muscles of the index and middle finger are paralysed. In these hands it is difficult to discover any problems in the motion of these fingers.[46] A mildly diminished extension of the DIP joint has been noticed in a few patients, which might be explained by the decreased extension force on the extensor apparatus.

The "lumbrical plus" is a situation in which there is a FDP tendon rupture distal of the lumbrical origin, or in the situation where a too long graft has been used. The FDP now pulls through the lumbrical muscle rather than through its tendon, causing PIP extension.[47]

1.2.3 Assessment possibilities (manual and instrumental)

Manual muscle strength testing (MMST) of the lumbricals is practically impossible because of the synergistic action of the interossei muscles. Strength testing is most likely less relevant than evaluating the co-ordination and dexterity in e.g. a tapping test when the lumbrical is paralysed and normal function. However, no studies have been found in which this has been utilised.

The strength can be measured in isolation of the interossei muscles in patients with an ulnar nerve lesion where the index and long fingers have only the lumbrical to maintain the intrinsic plus position. One study measured a mean MCP joint flexion strength in the index and long finger of 0.8 kg (range 0.3-1.5) compared with 6.4 kg (range 4.6-7.9) in the non-involved hand. Thus, the affected fingers have only about 12% of the strength of those of the non-involved hand.[46]

1.2.4. Therapy principles (prevention complications, strengthening, ADL)

No specific training/splinting program for lumbrical paralysis has been advocated. Strength training is similar to interossei muscle training, with perhaps more focus on speed and co-ordination.

2. Thenar muscles

The median nerve innervates the intrinsic thumb muscles that make the hand a "human" hand. These muscles oppose the thumb to the fingers: abductor pollicis brevis (APB), opponens pollicis (OP) and the flexor pollicis brevis (FPB). All these muscles originate from the flexor retinaculum and the trapezium carpal bone. Located in the thumb web the adductor pollicis (AP) is sometimes also considered a thenar muscle and will be discussed separately.

2.1 Abductor Pollicis Brevis (APB)

2.1.1 Functional anatomy

The insertion of the APB is at the radial side of the proximal phalanx of the thumb. Even though the APB is the smallest intrinsic thenar muscle, atrophy is quickly noticed as it is the most superficial muscle. The main function of the APB is moving the thumb away from the palm, in a perpendicular direction to the palm of the hand, when grasping objects. This is usually called palmar abduction of thumb, but in more recent terminology *anteposition* of the thumb.[48] The muscle is relatively weak as the action of abduction of the thumb is not one that is usually done against resistance; the APB "only" positions the thumb for action. This movement in the carpo-metacarpophalangeal (CMC) joint of the thumb is a synergistic action with the OP and, especially, the FPB.[49]

An extrinsic synergist of the APB is the abductor pollicis longus (APL). The pull of the APL on the CMC joint of the thumb causes palmar abduction, especially when the wrist is in flexion. Flexion of the wrist increases the moment arm of the APL due to bow stringing.[27]

Since the APB has a dual insertion into the base of the proximal phalanx and into the extensor tendon expansion, it also has an extension moment on the IP joint. After loss of the extensor pollicis longus (EPL) the APB together with the oblique head of the AP may provide complete extension of the IP joint of the thumb. This is clinically important when evaluating extension of the thumb and the EPL function.[50]

2.1.2. Pathokinesiology (paralyses, consequences for prehension/ADL, shortening)

Loss of the APB sometimes has little effect because the ulnar nerve innervated part of the FPB, the superficial head, can often move the thumb in palmar abduction by itself.[51] Frykman et al.[52] estimated that 50% of patients with a median nerve lesion would have satisfactory thumb opposition if no median nerve re-innervation occurred.

When the thumb can not be palmar abducted (anteposition) there will be problems with manipulating small objects and tip-tip pinch activities, but also in positioning the thumb to grasp larger objects. Rosen[53] found in 15 median nerve injured patients that of the 20 tasks of the Sollerman test, only a few tasks were particularly difficult: picking up coins from a purse, picking up nuts, putting on bolts, and fastening of buttons.

2.1.3 Assessment possibilities (manual and instrumental)

Because it is one of the few intrinsic muscles innervated by the median nerve, it is an important muscle in clinical practice e.g. to evaluate motor function impairment in median nerve compression in carpal tunnel syndrome. Unfortunately manual muscle strength testing in isolation is often hindered by the many synergists. Especially in the thumb, most movements are the product of multiple synergists.[11 30 54]

When testing the palmar abduction of the thumb, i.e. APB muscle strength, APL substitution can be diminished to a certain level by holding the wrist in extension. For strength testing, pressure is applied perpendicular to the palm of the hand at the MCP joint of the thumb[33] (Fig. 7).

Figure 7. Strength test of the abductor pollicis brevis (APB).

Several dynamometers that specifically measure the abduction strength of the thumb have been developed.[55-58] If these are not available the strength of the APB can be evaluated indirectly with a pinch dynamometer. We found a strong correlation between the pinch strength and the strength of the APB.[59] Weakness of the APB can cause a diminished pinch strength, mainly because the strong thumb muscles cannot be put into action to exert their full strength when the APB is not able to position the thumb.[36]

2.1.4 Therapy principles (prevention of complications, exercises for strengthening)

If the abduction of the thumb is weak (MRC < grade 3), there is a danger for thumb web (adduction) contractures, especially when ADL activities and/or work do not require opposition/abduction of the thumb. A night splint with thumb in maximum abduction is usually advised together with instructions how to maintain the mobility of the thumb web by pushing the thumb metacarpal away from the index, taking care not to push distal of the MCP joint (Fig. 8).

Figure 8. Prevention of thumb web contractures by pulling on the thumb proximal to the MCP joint of the thumb.

To assist in ADL several aids have been suggested: a weight to pull the thumb away from the index when the arm is in supination has been suggested by Wynn Parry.[60] An elastic sling, pulling the thumb into palmar abduction and a static or semi-rigid (neoprene) splint, which maintains the thumb web in a wide position can be tried out. These splints are usually not well accepted by the patient, due to the restrictions they cause and the cosmetic aspects.

Strengthening exercises for weak APB (< MRC 3) are to move the thumb towards the tip of index finger, including grasping large objects. Trick movements, e.g. of wrist flexion to activate the APL, are often difficult to un-learn. When MRC 3 is reached, all kinds of pinch exercises are useful besides handling large and small objects.

2.2 Opponens Pollicis (OP)

2.2.1 Functional anatomy

The OP originates from the trapezium and flexor retinaculum and, spiralling around the thumb, inserts into the radial border of the metacarpal bone of the thumb. The main function is to rotate the thumb and position the thumb towards the fingers, which is sometimes referred to as pronation. Moving the thumb towards the index or middle finger in an effort to pick up a coin from a smooth table, using the nails of both the thumb and finger and the need for the rotation of the thumb can be observed.

Another important function of the OP is its ability to stabilise the CMC joint with regard to the torsion moment in pinch movements.[27]

The moment arm of the ABP for abduction is increased by the OP because the OP pushes the APB up during its contraction.[27]

2.2.2 Pathokinesiology (paralyses, consequences for ADL / prehension)

OP muscle loss is often combined with other intrinsic thumb muscles, loss in isolation is very rare. Consequences for ADL are similar to APB loss.

2.2.3 Assessment possibilities (manual and instrumental)

In MMST the pressure is applied parallel to the palm of the hand at the CMC joint of the thumb, while no IP flexion of the thumb is allowed.[33]

Not a strength testing method but useful to evaluate the ability to position the thumb, the Kapandji 0-10 opposition thumb test is one in which the thumb is moved from the proximal phalanx of the index (“1”), to the tip of the fingers (“3, 4, 5 and 6”) and flexed along the little finger towards the distal palmar crease (“10”).[61] In a similar approach the opposition can be tested by having the patient touch the tip of the thumb to the tip of the little finger. At the end of the opposition, the thumbnails of the little finger and thumb, i.e. the distal phalanges, should be in one line.
Assessment of the OP strength with pinch meters is only indirectly possible. The RIHM is the only dynamometer which can test the OP more or less in isolation.[36]

2.2.4 Therapy principles (prevention of complications, exercises for strengthening)

The OP can be exercised by moving from the tip of the index finger towards the little finger, focusing on the pronation action of the thumb. Manipulating round objects, e.g. rolling a marble from the tip of the index finger towards the middle finger, can also be a helpful exercise. Rotation/supination of the thumb can also be trained with, e.g. for the right hand, unscrewing a nut and bolt.

2.3 Flexor Pollicis Brevis (FPB)

2.3.1 Functional anatomy

Similar to the AP, the FPB has two heads, but both have different innervation: the superficial part is usually median innervated and the deep head is ulnar innervated. The origin for the FPB is the flexor retinaculum and the trapezium, respectively. Comparable to the APB, the FPB inserts into the extensor tendon and the lateral sesamoid bone, and assists in extension of the IP joint of the thumb.

The proximal fibers of the FPB are continuous with the OP, therefore, both act on the CMC joint of the thumb and flex the metacarpal. The major effect of the FPB is in sequence with the AP, in that both flex the MCP of the thumb, although the FPB pronates and the AP supinates the thumb.[27]

2.3.2 Pathokinesiology (paralyses, consequences for ADL/ prehension)

Isolated weakness of the FPB is difficult to assess, not only because of the variations in innervation, but mainly because of all the synergists in flexion of the MCP joint and sometimes the lack of mobility in the MCP joint of the thumb. Isolated loss of the FPB might go unnoticed, but loss in combination with loss of the AP, e.g. in ulnar nerve palsy, will cause significant loss of pinch strength (see AP).

Positioning of the thumb in pinch activities is a median nerve muscle function, but the strength of the pinch grip is derived from the ulnar nerve innervated muscles.

2.3.3. Assessment possibilities (manual and instrumental)

In MMST the strength of the FPB is evaluated by the assessment of flexion at the MCP joint of the thumb without flexion of the IP joint, which is the FPL action. A strength test aiming to diminish the FPL action has been studied but without convincing results.[62]

Measurements of the strength of the FPB with pinch dynamometers in isolation is not possible. In the dynamometry of the pinch grip, the FPB together with the AP contribute significantly to pinch strength.

2.3.4. Therapy principles (prevention of complications, exercises for strengthening)

All pinch activities can be exercised, in which the tendency to (hyper-) extend the MCP joint is a sign of improper activation of the FPB and AP and needs to be corrected. A pinch whereby the MCP and IP joint is slightly flexed is also advantageous regarding the optimum (mid) position of the sarcomers of the intrinsic muscles of the thumb and for least tension on the soft tissues (ligaments, volar plate) of the thumb joints.

2.4 Adductor Pollicis (AP)

2.4.1 Functional anatomy

The ulnar innervated AP is a fanshaped muscle with two heads: an oblique part with its origin at the 2nd and 3rd metacarpals and the transverse part with its origin at the anterior surface of the 3rd metacarpal. The insertion of both heads is into proximal phalanx of the thumb and the sesamoid bone.

It is the most volar muscle in the thumb web, making atrophy visible in the palm of the hand. Of all the intrinsic muscles working on the thumb, the AP, working together with the FPB, has the largest flexion moment arm at the CMC joint. Therefore, the AP, together with the 1 DI, are the most important pinching muscle of the thumb, while other thumb muscles are just positioners and synergists.[27 p 229] The synergists for adduction of the thumb are EPL, FPL and the first dorsal interosseus.[63]

2.4.2 Pathokinesiology (paralyses, consequences for prehension/ADL, shortening)

Direct lesions of the AP sometimes occur after injuries into the thumb web, e.g. knife wounds. Paralyses of the AP usually occur after ulnar nerve lesion and therefore there is also weakness of the other important muscle for pinch; the 1 DI.

In ulnar palsy there may be enough median nerve innervated FPB to position the thumb for pinch, but when power is needed, the diminished AP strength usually results in hyperflexion of the IP joint of the thumb (Froment's sign) and sometimes in hyperextension of the MCP joint (Jeanne's sign).[27 p 54]

A patient who is bedridden for a prolonged time with little activity of the hand (coma etc.) can develop a thumb web contracture due to shortening of the AP. After a trauma of the hand, similar to the IT, shortening of the AP can take place. The AP rests in a compartment and therefore muscle tightness can cause severe thumb web contractures. Spasticity, causing a strong pull of the thumb into the palm can be seen in patients with cerebral palsy and who have suffered a stroke. The CMC joint is adducted, making it difficult to grasp or hold but also to release larger objects. In a surgical procedure releasing a considerable part of the AP is often necessary.

2.4.3 Assessment possibilities (manual and instrumental)

Tests are often described in which plain adduction of the thumb is tested. Due to the many synergists, this usually does not provide any useful information. Weakness or paralyses will result in loss of pinch strength and show the so-called Froment's sign. (Fig. 2). This was first described by Jules Froment, who was watching a train commuter reading his newspaper with one thumb flexed and the other straight.[64]

In examining the pinch strength of both hands, e.g. pulling on a piece of paper, the IP joint angle is observed: if more flexion occurs at the involved hand, the Froment sign is positive. When the MCP joint of the thumb has some laxity (hypermobile) into extension, hyperextension of the MCP joint of the thumb will take place in pinch, which is called Jeanne's sign.[21] Both are signs of a reduced flexion moment at the MCP joint of the thumb, i.e. weak or paralysed AP. Grading is not possible, besides a classification of a positive or negative sign.

Instrumental assessment of the strength of the AP can be done, indirectly, with pinch dynamometers.

2.4.4 Therapy principles (prevention of complications, exercises for strengthening)

Muscle strengthening exercises are all movements/activities where a pinch is needed, especially the key pinch or lateral pinch. If possible, pinch strength is trained with the thumb IP and MCP joints in slight flexion.

3. Hypothenar muscles

The muscles of the hypothenar are from ulnar to radial: abductor digiti minimi (ADM), flexor digiti minimi (brevis) (FDM), opponens digiti minimi (ODM). The palmaris brevis (PB) is the most superficial muscle overlying these muscles transversely and originates from the aponeurosis palmaris. All the hypothenar muscles are ulnar innervated. Isolated paralysis is rare and because there are functionally only minor differences between these muscles, they are discussed here as a group.

3.1 Functional anatomy

The most ulnar situated muscles (especially ADM) have the strongest ulnar abduction action of the little finger. The ODM, attached to the 5^{th} metacarpal bone, has an important role in the opposition of 4^{th} and 5^{th} rays. All the hypothenar muscles are active in the intrinsic plus position of the fingers, except for the ODM and the PB. In this position, similarly to the interossei of the fingers, they flex the MCP joint of the little finger and extend the IP joints.

3.2 Pathokinesiology (paralyses, consequences for prehension/ADL, shortening)

The 4^{th} and 5^{th} metacarpals are much more mobile in the CMC joints as compared to the 2^{nd} and 3^{rd}. This makes it possible to adjust the hand around a round object, but also e.g. the handle of a hammer. Flattening of the palmar arch of the hand (MCP joints) is another sign of weakness of the interossei and hypothenar muscles. The flexion of the 4^{th} and 5^{th} metacarpal bones at the CMC joints is diminished. This results in a flattening of the arch of the hand and in a weaker and less secure grip of the hand. (Fig. 9). The loss of cupping function of the hand can go unnoticed in many patients but, e.g. for people accustomed to eating with their hands, can cause some trouble.

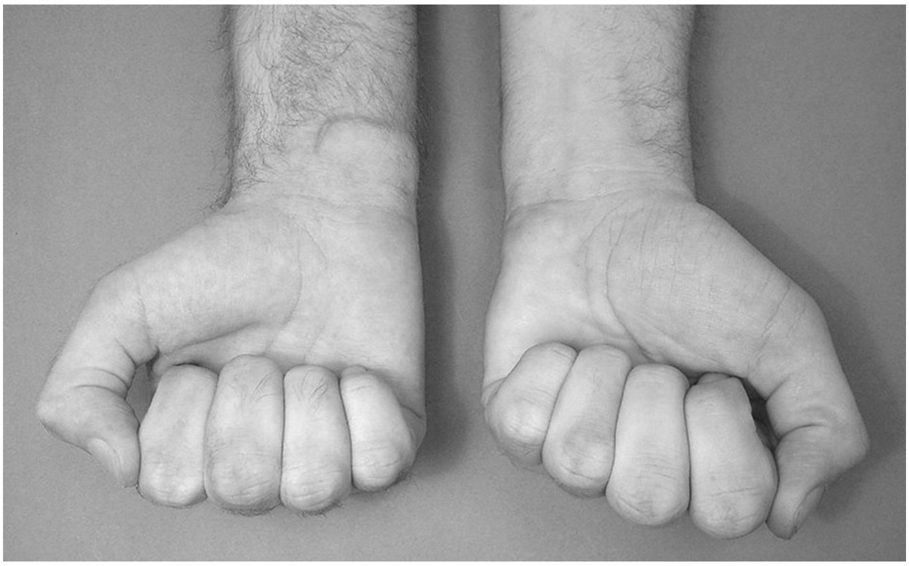


Figure 9. Loss of the metacarpal arch in a patient three months after ulnar nerve injury in right hand.

In patients in whom the ulnar nerve is paralysed a Wartenberg sign can be seen, which is usually described as a sign of activity of long extensor tendons of the little finger running radially of the MCP joint. The extensors produce an abduction force on the little finger which is not opposed by the paralysed intrinsic muscles.[65] In hands in which the ulnar nerve innervated muscles are recovering, the abducted position of the little finger often increases. In this situation we think it is also a sign of poor recovery of the third palmar interosseous muscle, in which the disbalance between the intrinsic abductors and adductors may cause an abducted little finger.

3.3 Assessment possibilities (manual and instrumental)

Due to the superficial location, the hypothenar muscles can be well observed and palpated during MMST.[34] This test is very useful to assess the recovery of the ulnar nerve function.[34] When testing the abduction of the little finger the ADM and FDM are tested. In the intrinsic plus position, pressing against the volar side of the PIP of the 5th finger, the same muscles can be tested as a group. ODM is tested in the cupping of the hand, when flexion of the CMC of the 5th ray is tested.

Instrumented measurements of the abduction strength of the 5th finger are possible with dynamometers such as the RIHM and Mannerfelt's Intrins-o-meter.

3.4 Therapy principles (prevention complications, strengthening)

Similar training activities as described for the interossei can be recommended. Grasping round objects emphasising the cupping of the hand is specifically trained, and specific attention is given to the shaping of the arch of the hand in grasping large objects and handles.

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CHAPTER 3

Strength of the intrinsic muscles of the hand measured with a hand-held dynamometer: reliability in patients with ulnar and median nerve paralysis

The whole arrangement in the finger shows perfect synchronism, each muscle and tendon doing its part, conserving its limited amplitude of motion and so relaying its action that by coordination with each other the complete motion is carried out.

Sterling Bunnell (1882-1957)
In: *Surgery of the Hand (1948)*

Reprinted from *Journal of Hand Surgery [British & European]* volume 25 (6): Schreuders TAR, Roebroeck ME, van de Kar ThHJ, Soeters JNM,

Summary

The aim of this study was to assess the reliability of a technique to measure the strength of the intrinsic hand muscles.

Intraclass Correlation Coefficients showed an excellent level of reliability for the comparison of muscle strength between groups of patients. However, for the results of individual patients, the calculated Standard Error of Measurements (10–16%) and the Smallest Detectable Differences for intraobserver (31-36%) and interobserver values (37-52%), indicate that only relatively large changes in strength can be confidently detected with this technique.

The results of the present study were compared with those of four previous grip strength studies.

Introduction

Many functions of the hand are derived from the intrinsic muscles of the hand. According to Ketchum et al.[1] loss of the intrinsic muscles causes an “awesome decrease” in functional efficiency of the hand. When the ulnar and/or median nerve is affected by injury, compression or by other neurological pathology, the intrinsic muscles of the hand are weakened or paralysed. Testing the strength of the hand muscles provides information for diagnosis, and for the assessment of the outcome of surgery and therapy. In view of the many recently developed techniques for nerve reconstruction (e.g. tubes, laser, glue, etc.)[2] it is important to have a precise, reproducible and standardised method of evaluating the muscle strength recovery.

Manual Muscle Strength Testing (MMST) according to the Oxford Medical Research Council (MRC) 0-5 Scale[3] is a method routinely used by physicians and therapists.[4] MMST is a reliable[5] and quick method but has two weak points. First, MMST produces an outcome that is difficult to quantify (ordinal scale). Second, the part of the MRC scale that corresponds with the MRC 3-5 range takes up almost the entire scale, and the sensitivity to change in this part of the scale is low.[6]

Quantitative measurements of muscle strength with grip and pinch meters may provide more accurate measurements of strength and may be more sensitive to change. Dynamometry is a popular means of expressing strength in a quantitative manner.[7-9] For example, grip and pinch strength measurements are used to determine the efficacy of hand therapy and surgical treatment.[10] Other instruments used are the MicroFET,[11] the sphygmomanometer[12], and the Citec hand-held dynamometer.[13] However, these instruments mainly measure the strength of the extrinsic muscles in the upper extremity and not the intrinsic muscles of the hand in isolation.[14] Mannerfelt[15 16] has developed an instrument which can measure the muscle strength of some intrinsic hand muscles, but Rosen[17] has reported that this instrument is difficult to handle and read.

Test-retest reliability is concerned with the extent to which an instrument yields reproducible results with repeated measurements under the same conditions.

Reliability can be expressed for the same observer (intraobserver reliability) and for different examiners (interobserver reliability). Reliability of measurements is a prerequisite for proper application in clinical practice.

The aims of this study were to evaluate a clinically applicable, objective method of measuring the intrinsic muscle strength in a quantitative way, and to determine intra- and interobserver reliability of these measurements in the hand.

Material and methods

The testing device was a lightweight (0.5 kg), battery operated, strain gauge dynamometer (Aikoh Model 9520A.B. Aikoh Engineering Co., Ltd. Tokyo, Japan) which is generally used for industrial precision measurements. The measuring range of the dynamometer, which records peak forces, is 0 kg to 20 kg, with an accuracy of 0.2%. A gutter shaped, 1.5 cm wide pad was custom made to match the shape of the finger and was fitted to the dynamometer (Fig.1).

Figure 1. Photograph of the modified dynamometer

We tested both hands of 24 patients with peripheral nerve lesions: there were 20 males, 4 females with age range 16 to 71 (mean, 39) years. All patients had undergone ulnar and/or median nerve repairs more than two years before the measurements. Of the 24 patients, nine had an isolated ulnar nerve injury, 12 a median nerve injury and three had both ulnar and median nerve injuries. The dominant hand was involved in 19 patients.

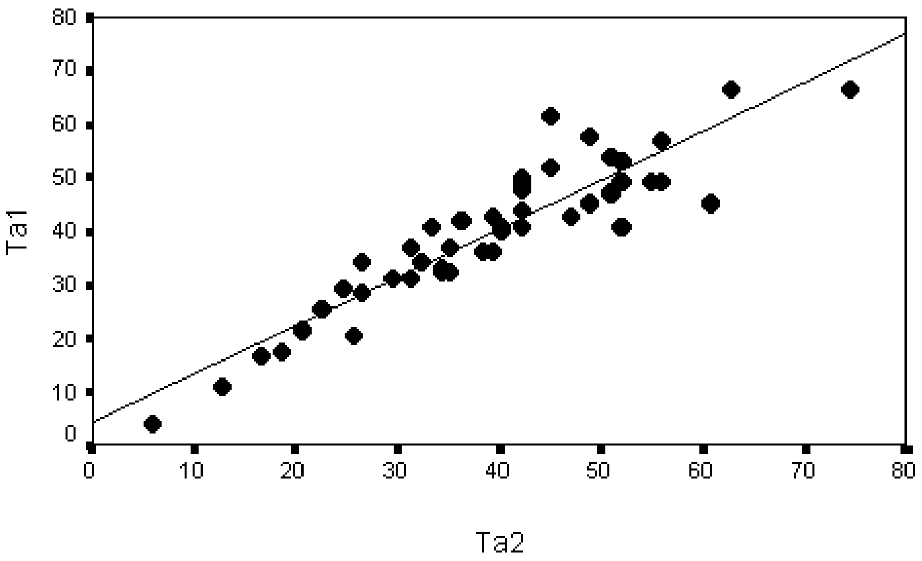
Manual Muscle Strength Testing (MMST) was done according to the Medical Research Council, 0-5 Scale.[3] The dynamometer measurements were made in a similar way to the MMST with respect to posture and the anatomical reference point where pressure was applied. The patient was seated at a table opposite the observer and given standard verbal instructions. The careful break test as described by Ketchum et al.[1] was used, in which the patient had to exert maximum force against the pad on top of the dynamometer. The examiner then exerts a little more force until movement (breaking) occurs. Within one session the strength of three movements were tested: for the ulnar nerve 1) the abduction of the little finger and the 2) index finger; for the median nerve 3) the palmar abduction of the thumb. The finger or thumb was placed in maximum abduction and the index and little finger MP joints were fully extended. The patient was then told to keep the finger/thumb in place. Pressure was applied at the proximal interphalangeal joint of the little and index finger and the metacarpo-phalangeal joint of the thumb. The order of a testing session was always the same: abduction of the little finger, abduction of the index finger and finally the abduction of the thumb of the injured, and then the uninjured, hands. For each test the mean of three peak values was calculated.

The tests in each patient were all done on the same day and did not take longer than 45 minutes. The test sessions were first done by one observer (TARS = Ta1) and directly after this the second observer (JNMS=Tb) did the same tests without knowledge of the results of the first session; finally the first observer repeated the dynamometer measurements once again (Ta2).

Data Analysis

Statistical analyses were performed to determine intraobserver (between Ta1 and Ta2) and interobserver (between Ta1 and Tb) reliability. For each of the three movements separate analyses were performed, using data of both the injured and non-injured hands (n=48). This analysis provides one reliability index for each movement, referring to a broad range of muscle force; from paralysed to normal force levels. The use of one reliability index is preferable for the application of measurements in clinical practice. Because patients will be measured over time with force increasing from low to almost normal. Secondly, ratios of the muscle force of the injured hand versus those of the non-injured hand of a patient are frequently used in interpreting muscle strength.

Figure 2. scatterplot of repeated (intraobserver) measurements



The scatterplot (Fig. 2) of repeated (intraobserver) measurements showed a fan-shaped appearance, implying that the amount of error variance between the first and second measurement was associated with the magnitude of muscle force. Therefore, a logarithmic transformation of the data was performed prior to further analysis. On the transformed data Analysis of Variance (ANOVA) was performed with a SPSS/PC+ program to determine the multiple sources of measurement error, which were calculated as the percentage of the total variance. The variance attributed to differences between patients and tester, also including some residual error from non-specified error sources was designated Var (P). Var (T) is the variance attributed to differences between sessions by the same tester (Ta1 and Ta2); and different testers (Ta1 and Tb); and Var (PxT) is the variance due to interaction between patient and tester.

Intraclass Correlation Coefficients (ICC) were computed as the ratio between the variance between patients, i.e. Var (P), and the total variance, i.e. the sum of Var (P), Var (T) and Var (PxT). The last two components, i.e. Var (T) and Var (PxT) constitute the error variance. From the error variance the Standard Error of Measurement (SEM) is computed as its square root. Based on the SEM the Smallest Detectable Difference (SDD) is calculated as $1.96 \times \sqrt{2} \times SEM$. By back-transforming the results, antilogs of the SEM and SDD provide proportional indexes of measurement error, which are expressed as percentages of the measurements.

Results

For all three movements tested (i.e. abduction of little finger, abduction of index finger, and palmar abduction of thumb) mean values and SD were calculated. This was done for the injured hands (n=24) and non-injured hands (n=24) separately, as well as for both hands combined (n=48) (Table 1).

Table 1. Intrinsic muscle strength (Newton) measured with the modified dynamometer.

	Session	**Ta1**	**Ta2**	**Tb**
Injured hands	Little finger	24.3	24.2	27.5
	(n=12)	(12.3)	(10.5)	(14.8)
(n=24)	Index finger	44.7	47.3	41.9
	(n=10)	(30.7)	(27.7)	(28.7)
	Thumb	51.2	52.6 29.8)	52.2
	(n=15)	(30.9)		(31.7)
Non-injured hands	Little finger	45.3	44.5 (12)	45 (13.8)
		(10.2)		
(n=24)	Index finger	77.4	79.6	70.4
		(19.8)	(19.7)	(15.8)
	Thumb	108.7	103.3	99.4
		(29.4)	(27.2)	(24.9)
Both hands	Little finger	40.0	39.4	41.7
		(13.6)	(13.7)	(15.4)
(n=48)	Index finger	71.0	72.7	65.2
		(25.3)	(24.2)	(21.9)
	Thumb	88.1	85.1	82.6
		(37.9)	(35.4)	(33.9)

n = number of hands. Data are mean and standard deviation (SD) of sessions by the first tester (Ta1 and Ta2) and the second tester (Tb). Three groups are presented: 1. data on the muscles with ulnar and/or median nerve paralysis; 2. Data on all the non-injured hands (n=24); 3. Data on both hands of each patient (n=48).

For the hands with an ulnar nerve injury (n=12), measurements with the dynamometer showed that the mean strength of the little finger abduction was 25.3 N (range 3.9-57.8) and of index finger abduction was 44.6 N (range 10.8-108.8). For the hands with a median nerve injury (n=15) the mean strength of the thumb abduction was 52 N (range 12.9-123.9). The recovery of muscle strength was also calculated as a percentage of the non-injured hand. The mean value for recovery of the little finger abduction was 57%, index finger abduction 58% and for thumb abduction 50%. The mean muscle strength according to the MRC scale for the little finger abduction was 4.2, index finger abduction 3.5, and thumb abduction 3.6.

Analysis of variance (ANOVA) showed that the sources of measurement, i.e. the variance between test sessions (Var T) and the variance due to interaction between patient and test session (Var PxT) contributed 4.2-9.1% to the total variance (Table 2). The largest part of the error variance was attributed to the interaction between patient and test session. This implies that some patients produced the highest forces in the first test session or with the first tester, whereas others performed better in the second test session or with the second therapist.

Table 2. Intrinsic muscle strength measurements (mean) of both hands of 24 patients with ulnar and/or median nerve paralyses, and variance (%) indicating reliability.

	Little finger abduction		**Index finger abduction**		**Thumb abduction**	
	Intra-observer	Inter-observer	Intra-observer	Inter-observer	Intra-observer	Inter-observer
Mean(N)	39.7	40.9	71.9	68.1	86.6	85.3
Var(P)	95.7%	90.9%	94.9%	90.9%	95.8%	95.9%
Var(T)	0%	0%	0.1%	1.1%	0%	0.5%
Var(PxT)	4.3%	9.1%	5%	8%	4.2%	3.7%

Mean is given in Newton (N), all other data after logarithmic transformation. Analysis of Variance: where Var(P) = variance to be attributed to differences between patients. Var (T) = variance attributed to differences between tests by same observer (Ta1 and Ta2), and between different observers (Ta and Tb), and Var(PxT) = variance due to interaction between patient and tester.

The intraclass correlation coefficients (ICC) for both intra- and interobserver reliability are given in Table 3. For all three movements, ICCs were greater than 0.90. This indicates that the force measurements are very reliable as far as differences between groups of patients are concerned.

Table 3. Intraclass Correlation Coefficient (ICC), Standard Error of Measurement (SEM) and Smallest Detectable Difference (SDD) of strength measurements of the intrinsic muscles of the hand.

	Little finger abduction		**Index finger abduction**		**Thumb abduction**	
	Intra-observer	Inter-observer	Intra-observer	Inter-observer	Intra-observer	Inter-observer
ICC	0.96	0.91	0.95	0.91	0.96	0.95
SEM	10%	16%	11%	15%	12%	12%
SDD	31%	52%	32%	46%	36%	37%

For the interpretation of measurement results of individual patients, the SEM and SDD inform us about the amount of measurement error that should be taken into account. For the movements tested the SEMs and SDDs are presented in Table 3, which show that the intraobserver values are smaller than the interobserver values. SEMs range from 10-16%, and the SDDs for intraobserver values range from 31-36% and for interobserver values from 37-52%. This implies that for individual patients with the same tester, between consecutive measurements, only differences greater than 31-36% may be interpreted as real change.

Finally, the SEM and SDD results of the present study were compared with those of several earlier grip strength studies (Table 4).

Table 4. Data on grip strength measurements from earlier reliability (intra observer) studies compared with data from the current study.

Study	Handheld dynamometer	Unit	subjects		N	Mean	SD	ICC	SEM	SDD	% of mean
Boissy	Lafayette grip	N	Healthy		10	381.7	87.3	0.86	33	91.5	24%
			Stroke		15	130.3	83.7	0.91	25	69.3	53%
Geertzen	Citec	N	RSD	unaffected hand	29	123	66	0.97	24	66	54%
				affected	29	84	51	0.94	25	71	85%
Nitschke	Jamar	kg	Healthy women		32	32.5	6.9	0.93	1.8	5.7	18%
			Women with NSRP		10	17.4	6.2	0.95	1.4	5.9	34%
Spijkerman	Grip gauge	Nm	Healthy		16	43.3	9.9	0.98	1.4	3.9	9%
			Injured hands		8	23.1	17.7	0.98	2.5	6.9	30%
Schreuders	AIKOH intrinsic dynamometer	N	Peripheral nerve injured	abduction dig 5		40	13.6	0.96	10	31%	
				abduction dig 2	48	71	25.3	0.95	11	32%	
				abduction thumb		88.1	37.9	0.96	12	36%	

N = Newton; Nm = Newton meters; n= number of subjects; NSRP = Non- specific regional pain syndrome; ICC = Intraclass correlation coefficient; SEM = standard error of measurement; SDD = smallest detectable difference; % of mean = SDD percentage of the mean.

Discussion

In practically all studies evaluating peripheral nerve function, grip and pinch strength are measured. However, grip strength measurements do not necessarily provide useful information about the motor function of the ulnar and median nerve in the lower arm. Patients with a complete ulnar nerve lesion can have a considerable grip strength, evidently because the extrinsic muscles are not paralysed. In our opinion, grip and pinch strength measurements provide information on the combined function of all the muscles of the hand, including the wrist extensors innervated by the radial nerve. In addition, generally the peripheral nerves are injured in combination with one or more injuries of the finger and wrist tendons. In such cases it is even more difficult to determine the contribution of the intrinsic muscles to the total amount of grip strength.

An attempt to analyse the contribution of the intrinsic muscles to grip and pinch strength was made by Kozin et al.[18] They measured a 38% decrease in grip strength after ulnar nerve block and a 32% decrease after median nerve block. The only median innervated intrinsic muscles contributing to grip are the two lumbrical muscles to the index and middle finger. It is questionable whether two small lumbricals can contribute as much as 32% to grip strength. Apparently, grip strength measurements show changes after nerve paralysis but it is difficult to determine whether this is due to loss of extrinsic or intrinsic muscle strength, or perhaps due to loss of sensory function.

In the present study we evaluated a device that we modified to measure the strength of the intrinsic muscles in isolation. The first step in assessing this new method is to establish the reliability of these measurements.[7]

The intraobserver and interobserver reliability calculated as ICCs was high. This indicates good reliability of the measurements when used to compare groups of patients. For the purpose of measuring individual patients to assess changes in muscle strength over time, however, the standard errors of measurement (SEMs) and the smallest detectable differences (SDDs) are appropriate indexes of measurement error. These provide information about the width of the error band around a measured value and in the amount of measurement error that should be taken into account when comparing two consecutive measurements.[19 20] The relatively large values that we found for these indices in the present study implies that the reliability of the force measurements for assessing changes in individual patients is less satisfactory than for groups of patients. Only changes of more than 30% to 50% in muscle force in a patient can be interpreted as real changes. It is questionable whether this amount of measurement error is satisfactory when assessing clinically relevant change in patients with hand and nerve injuries.

As we are unaware of any study concerning the reliability of intrinsic muscle strength measurements, we compared the SEM and SDD results of the present study with those of earlier grip strength studies.[13 21-23]
Because we used a log transformation the outcome was a SDD percentage. The data from the other studies did not use the log transformation, and thus the SDDs are in the original unit of measurement. To allow comparison of the SDDs from these latter studies with our results, we assessed the SDD as a percentage of the mean (Table 4). It was found that in intra-tester reliability studies with normal subjects the percentage of the SDD of the mean, (in Table 4 "% of mean"), was 9-24% (mean 15%). The SDD as percentages of the mean in the different patient groups were between 30-53% (mean 39%). Geertzen et al.[13] also studied the intra-tester reliability of grip strength in Reflex Sympathetic Dystrophy (RSD) patients and found large SDDs of 66 N in the unaffected hand (54% of mean) and as high as 84.5 N (85% of mean) in the affected hands. Geertzen and colleagues concluded that their reliability study of muscle strength measurements in RSD patients gives values which should be "treated with scepticism". Except for Geertzen's group, all other studies concluded that the intra-tester reliability was satisfactory.

From our clinical experience we assume that an SDD of 30% or larger is not sufficient to assess clinically relevant changes in patients with hand and nerve injuries. The SDD for inter-tester reliability of 37-52% leads us to conclude that we would not recommend this dynamometer to be used by different testers for measurements in the same patient.

To further reduce the amount of measurement error we suggest that the shape of the dynamometer be modified because it was not designed for hand-held measurements and is cumbersome to use. Secondly, because a small change in the angle of pushing between the device and the finger causes large differences in the recorded strength, measurement made by pulling on a string, rather than pushing the device against the device, might improve the reliability.

Adaptations to the device, and the elucidation of the relationship between grip strength, MMST and the dynamometry of the intrinsic muscles of the hand, will be the focus of future studies.

Conclusions

The hand-held dynamometer used in this study to measure the strength of the intrinsic muscles of the hand after peripheral nerve lesion has excellent reliability for comparing muscle strength between groups of patients. However, the Smallest Detectable Difference (SDD) of the measurements of the thumb, index and little finger indicate that only with relatively large changes in measurements can a clinician be confident that real changes in muscle strength have occurred.

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CHAPTER 4

Strength Measurements of the Lumbrical Muscles

In the palm of the hand, and between the metacarpal bones, are numerous small muscles, (lumbricales and interossei) which perform the finer movements, – expanding the fingers, and moving them in every direction with quickness and delicacy. They are the organs which give the hand the power of spinning, weaving, engraving etc; and as they produce the quick motions of the musician's fingers, they are called by anatomists ***fidicinales.*** *(= of or relating to a stringed instrument)*

Charles Bell *(1774-1842)*
The Hand - Its Mechanism and Vital Endowments as Evincing Design (1833)

Reprinted from *Journal of Hand Therapy,* Vol. 9, Schreuders TAR, Stam HJ. Strength measurements of the lumbrical muscles. P 303-305,

Abstract

This study was designed to measure the strength of the lumbrical muscles in the index and long fingers in patients with ulnar nerve paralysis. A hand-held dynamometer was used.

The results show that in ulnar nerve damage the index and long fingers have a mean metacarpo-phalangeal (MCP) joint flexion strength of 0.8 kg (range 0.3-1.5), compared with 6.4 kg (range 4.6-7.9) in the non-involved hand. Thus, the damaged fingers have only about 12% of the strength of those of the non-involved hand. In the hand with ulnar paralysis, the loss of intrinsic strength (dorsal and palmar interosseous muscles) is considerable (almost 90%).

The contribution of the interosseous muscles in maintaining the intrinsic position is considerably greater than that of the lumbricals. Comparing the Medical Research Council (MRC) scale (0-5) with the dynamometry measurements shows that MRC grade 3 correlates with about 0.8 kg, while grade 5 correlates with about 6.5 kg of MCP joint flexion strength.

Introduction

The lumbrical muscles are the only muscles whose origin and insertion are tendons: the flexor digitorum profundus (FDP) and the extensor expansion of the extensor digitorum communis (EDC), respectively.

There is no consensus about the role of the lumbrical muscles.[1] Several studies[2-13] have documented the strength of the lumbricals in normal subjects, but only a few studies have investigated the strength of the intrinsic muscles after complete ulnar nerve lesion.[9] Patients with paralysis of an isolated ulnar nerve normally show clawing of the fourth and fifth fingers; this is characterised by an inability to extend the proximal interphalangeal (PIP) joint and by hyperextension of the metacarpo-phalangeal (MCP) joint. The lumbrical muscles of the second and third fingers are innervated by the median nerve and prevent these fingers from clawing. Thus, in cases of ulnar nerve paralysis it is possible to study the lumbrical muscles separately from the other intrinsic muscles.

Knowledge about the actual strength of the lumbrical muscles in patients with ulnar nerve paralysis enables us to better understand the function of the lumbricals and other intrinsic muscles. Moreover, this knowledge may help to develop a more rational basis for therapeutic and surgical techniques.

Material and Methods

Twelve patients (one female, 11 males; age range: 18-62 years; mean: 32 years) with complete traumatic ulnar nerve paralysis were tested with a lightweight industrial dynamometer gauge (Model 9520A.B; Aikoh Engineering Co., Ltd., Tokyo, Japan) with a measuring range of: 20 kg and an accuracy of 0.2%. A gutter-shaped pad, 1.5 cm wide, replaced the standard accessories. The testing procedure was similar to the Manual Muscle Strength Testing procedure devised by Brandsma et al.[14] The patient was seated, with the elbow resting on a table and the forearm in a vertical position; the hand was held in the intrinsic-plus position (i.e., with the MCP joints flexed and the PIP joints extended) (Fig. 1).

Figure 1. AIKOH dynamometer gauge

The testing device was placed on the volar aspect of the PIP joint of the second and third fingers, and force was increased until the PIP joint flexed. This isometric strength test has been described as a "careful break test." In the present study the mean value of three measurements in each finger was calculated. Studies by Long[4] and by Landsmeer[15] have shown that in this position the extrinsic flexors have a minimal influence on MCP flexion.

Manual Muscle Testing (MMT) using the Modified Medical Research Council (MRC) scale (Table 1) was performed on all fingers of both hands in all 12 patients.

Table 1.

Modified Medical Research Council Scale

Grade	**Resistance**	**Range of Movement**
5	Normal	Normal
4	Normal	Reduced
3	Normal	None
2	Reduced	None
1	None	Palpable contraction only
[illegible]	[illegible]	[illegible]

Results

Table 2 presents the results of the strength measurement tests in the individual patients. It is clear that patients with ulnar nerve paralysis had barely sufficient strength to maintain the intrinsic-plus position.

Table 2. Strength (kg) of the intrinsic muscles in the second and third fingers of the ulnar paralysed hand and in normal digits patients age injured hand noninjured hand (n = 12)

		Injured hands		Noninjured hands	
Patient (n=12)	**Age (years)**	**digit 2**	**digit 3**	**digit 2**	**digit 3**
DeJ	32	1	0.9	7.2	7.9
G	36	0.9	1.1	5	5.5
D	62	0.6	0.7	6.2	6.5
R	25	0.7	0.5	5.2	5.5
VdH	45	0.7	0.7	5.8	4.6
F	31	0.3	0.4	7.1	5.7
VdL	30	0.6	0.8	7	5.7
K	23	0.9	0.3	5.6	6.5
S *	18	0.4	0.6	6.9	7.3
Z	43	1	1.2	7.2	7.8
P	46	1.3	1.5	6.9	7
VH	34	1	0.8	7	6.3
Mean	32	0.8	0.8	6.4	6.4

* The only female patient in the group

The mean value of the strength of the two digits of the injured hand was the same, as was the case in the noninjured hand: 0.8 kg (range 0.3-1.5) and 6.4 kg (range 4.6-7.9), respectively.

Based on the MRC scale, all injured digits were grade 3, whereas the fingers of the noninjured hand were grade 5.

Discussion

The intrinsic muscles are of paramount importance for efficient hand function. The lumbrical muscles differ from other muscles in that they both originate and insert at tendons. There are several different theories about the function of the lumbrical muscles but no consensus.[1]

According to Jacobson et al.[5] the lumbricals have an extremely small physiologic cross-sectional area (PCSA), but they have long muscle fibres. Jacobson et al. concluded that lumbricals are designed for high excursions and velocity production. Backhouse et al.1954[6] and Long[7] performed electro-myographic studies of the lumbricals and concluded that their principal action is extension of the interphalangeal (lP) joints and weak flexion of the MCP joints. Ranney and coworkers[1] came to the same conclusion based on biomechanical studies of the lumbricals in human cadavers. Ketchum et al.[9] calculated the mean force of the lumbricals and estimated it to be approximately 14% of the total force flexing the MCP joints; they estimated that the contribution of the lumbricals to resisted movement is 2.03 ± 0.9 kg.

Brand[10] reported that at the lP level the lumbricals act as extensors, as do the interosseous muscles. Furthermore, the lumbricals diminish the flexion moment of the profundus tendons at the same joint by diverting FDP force to the extensor expansion. During flexion, the lumbricals may dominate the sequence of closure and ensure that the MCP joints flex ahead of the lP joints, allowing the hand to surround a large object. The lumbricals also co-ordinate finger movements. Devanandan et al.[11] found that the lumbricals contain an unusually high number of muscle spindles, which are important for proprioception of the fingers and hands.

Leijnse and Kalker[12] concluded that the lumbricals are in an optimal position for proprioceptic feedback concerning the position of the PIP-distal interphalangeal (DIP) joint mechanism due to the large systematic moment arm at the lP joint level and the very small systematic moment arm at the MCP joint. They also formulated the role of the lumbricals in the so-calIed lumbrical loop, in which the lumbricals control the PIP and DIP joints, and the EDC and FDP control the MCP joint. This movement may be the basis of fast movements in, for example, a musician's hand.

Many different methods exist for surgically reconstructing a claw hand after ulnar nerve paralysis.[16] These methods include intrinsic replacement, lumbrical replacement, or MCP flexor replacement. Currently, it is recommended that all four fingers be corrected,[17] but some clinicians suggest that correction of only the fourth and fifth digits is sufficient.[13]

Objective measurement of intrinsic muscle force is necessary for three reasons. First, it is important to establish the relative contribution of the interosseous muscles and the lumbricals to the balance of forces in the hand. Second, measurements are required to monitor the recovery of strength in patients with paralysis following ulnar nerve lesions Third, if reconstructive surgery is considered, it is important to know the required strength of the muscles involved.

Specific testing of the intrinsic muscles can be done manually.[14] Manual Muscle Testing according to the Oxford Medical Research Council's 0-5 Scale (MRC scale)[18] is routinely used by therapists. Dynamometry is a popular means of expressing strength in a quantitative manner.[19-21] For example, grip and pinch strength measurements are used to determine the efficacy of hand therapy and surgical treatment.[22] However, most devices have been designed to measure extrinsic muscle strength of the long flexors. The intrinsic muscles are not necessarily tested by grip and pinch strength measurements.

In the present study, the strength of index and long fingers with an ulnar nerve lesion correlated with grade 3 on the MRC scale in all 12 patients. In MRC terms, this means that the strength is considered "reasonable," or 50%, on a 0%-100% scale.[23 24] The actual strength, however, as measured by the dynamometer was only 12% of the strength of the noninjured hand. Therefore, we concluded that an MRC grade 3 for the intrinsic muscles is comparable with 12% (and not 50%) of normal strength.

The loss of 90% of intrinsic muscle strength suggests that the primary role of the lumbricals is not to produce power but rather to divert strength from the FDP and to contribute to the sensory feedback for co-ordination. Evidently, the interosseous muscles are much stronger than the lumbricals. The strength of the lumbricals is not sufficient to withstand clawing, and latent clawing of the index and long fingers in the hand with ulnar paralysis must be kept in mind.[10]

Applying extension force to the MCP joints of these digits will cause them to collapse into a typical claw deformity. Splinting only the fourth and fifth fingers will in many cases be inadequate because clawing may develop in all four fingers. When training and testing intrinsic muscles, it is important for hand therapists to be aware of the biomechanics of the lumbrical and interosseous muscles and their respective contributions to the prevention of clawing in the hand with ulnar nerve paralysis.

Conclusions

The mean strength of the lumbricals after an ulnar nerve lesion is 0.8 kg, which is about 12% of the intrinsic muscle strength of the normal hand. There was no difference between the mean values of the strength of the index and long fingers after ulnar nerve paralysis. When reconstructive surgery is considered to correct a claw hand, the loss of strength (almost 90%) in the index and long fingers should be taken into account.

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CHAPTER 5

Measurement Error in Grip and Pinch Force Measurements in Patients with Hand Injuries

From error to error, one discovers the entire truth
Sigmund Freud *(1856-1939)*

Reprinted from Schreuders TAR, Roebroeck ME, Goumans J, van Nieuwenhuijzen JF, Stijnen TH, Stam HJ. Measurement error in grip

Abstract

There is limited documentation of measurement error of grip and pinch force evaluation methods. The purposes of this study were (1) to determine indexes of measurement error for intraexaminer and interexaminer measurements of grip and pinch force in patients with hand injuries and (2) to investigate whether the measurement error differs between measurements of the injured and noninjured hands and between experienced and inexperienced examiners.

The subjects were a consecutive sample of 33 patients with hand injuries who were seen in the Department of Rehabilitation Medicine of Erasmus MC–University Medical Center Rotterdam in the Netherlands. Repeated measurements of grip force in 2 handle positions. The time between two measurements and change of examiners was 2-3 minutes. For the grip force the distance between handles were 4.6 and 7.2 cm, respectively and of tip pinch, with the index finger on top and the other fingers flexed with the thumb below and key pinch force, with the thumb on top and the radial side of the index finger below were obtained on both hands of the subjects by an experienced examiner and an inexperienced examiner. Intraclass correlation coefficients (ICCs), standard errors of measurement (SEMs), and associated smallest detectable differences (SDDs) were calculated and compared with data from previous studies.

The reliability of the measurements was expressed by ICCs between .82 and .97. For grip force measurements (in the second handle position) by the experienced examiner, an SDD of 61 N was found. For tip pinch and key pinch, these values were 12 N and 11 N, respectively. For grip force measurements by the inexperienced examiner these values were 56 N for grip force measurements and for tip pinch and key pinch, 13 N and 18 N, respectively

Based on the SEMs and SDDs, in individual patients only relatively large differences in grip and pinch force measurements can be adequately detected between consecutive measurements. Measurement error did not differ between injured and noninjured hands or between experienced and inexperienced examiners. Criteria for judging whether the measurement error does allow application of the measurements in individual patients are discussed.

Introduction

Only data that have acceptable reliability and validity are valuable in the clinical decision-making process for determination of impaired function and comparison of surgical repair techniques to document progress during rehabilitation and to evaluate disability after injury. Such data will decrease the need for use of unsubstantiated opinions and will increase the physical therapist's ability to obtain reproducible findings and meaningful results.[1] Better reliability implies better precision of single measurements, which is a prerequisite for better tracking of changes in measurements in research and clinical practice.[2]

Generally accepted instruments in the evaluation of hand function measure grip and pinch force. Grip and pinch force measurements have been promoted as an important measure of outcome in, for example, the evaluation of peripheral nerve function.[3-5]For a correct interpretation of these force measurements, we contend information on the reliability (measurement error) of these measurements is required. The reliability of grip force measurements has been studied in patients with hand injuries[6 7] and in people without impairments of the hand.[8 9] It also has been studied in several other categories of patients, including women with non-specific regional pain (NSRP)[10] and patients with reflex sympathetic dystrophy (RSD)[11] or epicondylitis,[12 13] and in people after a stroke.[14] The reliability of pinch force measurements has been studied in patients with RSD[11] and repetitive strain injury (RSI).[15]

The studies of Spijkerman et al[6] and Brown et al[7] on the reliability of force measurements in patients with hand injuries have important drawbacks. The study by Spijkerman et al included only 8 patients, and Brown et al, in their study of grip and pinch force measurements in patients with hand injuries, did not specify the measurement error. As in many studies, the intraclass correlation coefficient (ICC) was used as a measure of reliability. For clinical use, however, we believe the most relevant information is the magnitude of change between tests that is required to detect a real change, preferably quantified in the same units as the force measurement.[10 16] This magnitude of change is specified in the smallest detectable difference (SDD), which is calculated from the standard error of measurement (SEM), the absolute error component of the measurements.[17 18] The smaller the measurement error, the better the measure.[19]

Various factors relating to the patient's condition may influence the measurement error, such as the amount of pain and loss of normal function of the fingers or thumb after injury. The experience of the examiner also might influence the measurement error. However, studies on these aspects of grip and pinch force measurements for patients with hand injuries are scarce.

One aim of our study was to assess the SEM and related indexes of reliability for intraexaminer and interexaminer applications of grip (2 handle positions, with distances between the handles of 4.6 and 7.2 cm) and pinch (tip pinch and key pinch) force measurements for patients with hand injuries obtained with Lode handgrip and pinch-grip dynamometers (Figure 1).

Figure 1. Measurements were performed with the participant seated at a table on which the dynamometers were positioned.

A second aim was to investigate whether the measurement error of grip and pinch force measurements differs between specific applications, such as measurements of injured and noninjured hands, measurements obtained by experienced and inexperienced examiners, and measurements between 2 handle positions for grip force and 2 different types of pinch force (i.e., tip and key pinch force). A third aim was to judge whether the measurement error is small enough to justify use of these measurements to discern real changes in grip and pinch force in individual patients. Because no clear criteria to judge the SDD are available for grip and pinch force measurements, we compared our findings with the results of studies in which grip and pinch force measurements were examined in different patient categories, i.e. patients with hand injuries, women with pain (NSRP), RSD, epicondylitis and after a stroke.

Method

Subjects

A consecutive sample of 33 patients (20 male, 13 female) who were seen in the Department of Rehabilitation Medicine of Erasmus MC-University Medical Center Rotterdam in the Netherlands participated in the study. They had a mean age of 36 years (SD=13.7, range 17-67).

All patients had an injury on only one hand (6 with tendon lacerations, 9 with nerve lesions, 4 with fractures, and 14 with a combination of lesions or surgeries e.g., crush injury, finger amputation, arthrodesis). During a period of 5 months, patients who were capable of being evaluated for grip and pinch force were asked to participate in this study. Patients who were not permitted to grip or pinch with maximum force because of injured tissue and patients who complained of pain were excluded. We presumed that pain would inhibit the patients from exerting full maximum force and that force measurements may reflect the amount of pain rather than the force-generating capacity of the patients. We acknowledge that excluding those patients limited our study to only those patients who were pain-free. The participants were informed about the purpose of the study and gave informed consent.

The participants were in different phases of their rehabilitation process. Study entry was, on average, 22 months after injury or surgery when including one patient who had a 16-year period between the date of injury and time of examination. Excluding this patient, the average period was 9 months (SD=7.0, range 1-28) since injury or surgery. Force measurements of the hand are routinely obtained in our department during different phases of the rehabilitation process. Such measurements can be used to determine progression of muscle force recovery, the ability to perform in a vocation, and indications for continuing therapy and to assess long-term outcome after hand injuries.

Instrumentation

We used Lode handgrip and pinch-grip dynamometers* (Fig. 1). The distances between the handles of the Lode handgrip dynamometer were adapted to create spaces between the handles comparable to those of the Jamar hand dynamometer.†[,20] For our study, the grip handle positions 2 (distance between handles=4.6 cm) and 4 (distance between handles=7.2 cm), which we designated "grip 2" and "grip 4," respectively, were used with the handgrip dynamometer.

With the Lode pinch-grip dynamometer, which is similar in design to the Preston† pinch dynamometer,[21] 2 types of pinch were measured: tip pinch and key pinch. Tip pinch force was measured with only the index finger on top and the other fingers flexed with the thumb below, and key pinch force was measured with the thumb on top and the radial side of the index finger below.

* Lode Medical Technology, Zernikepark 16, 9747 AN Groningen, the Netherlands. Distributed in the United States
by ElectraMed Corp, G-5332 Hill-23 Dr, Flint, MI 48507.

† Sammons Preston/Rolyan, 4 Sammons Ct, Bolingbrook, IL 60440.

The grip handle is connected to an amplifier from which the values give a digital readout on a display. According to the manufacturer, the measuring range is 0 to 1,000 N, with an accuracy of 1% deviation for 2 to 500 N and 2% for 500 to 900 N. Calibration was done with suspended weights according to the method described by Mathiowetz et al.[8] We believe the use of strain gauge technology is preferable to dynamometers which are spring-based or use a hydraulic pressure system, because such dynamometers might produce erroneous data due to the wear and tear of metal, slow leaks and hysteresis.[22]

Procedure

Measurements were taken according to recommendations of the American Society of Hand Therapists (ASHT).[22] Participants were seated at a table on which the dynamometers were positioned (Fig. 1). The subjects were told to keep their elbow flexed without resting their arm or the grip device of the dynamometer on the table. The digital display was not visible to the subjects. Corresponding to the ASHT recommendations for each measurement, the mean of 3 measurements was recorded. Measurements were obtained of the left and right hands alternately, which is the method of testing used at our clinic. Testing both hands, we contend, enables comparisons of the injured and noninjured hands, as proposed by Gaul.[23]

The side (injured or noninjured) at which measurements were started and the order of tests (grip 2, grip 4, tip pinch, or key pinch) were randomly selected. Both examiners obtained all the measurements twice for each subject; the order of examiners was randomly selected. During each measurement session, the examiners obtained 12 measurements (2 grip and 2 pinch measurements × 3 repetitions from one hand). Then the examiners were changed while the subject took a short break (2-3 minutes) and moved the arm and hand out of the testing position. In this way, we attempted to reflect practice with examiners independently testing subjects, except there was a short time interval between examiners. Both examiners participated in 2 sessions per patient, which resulted in 48 measurements per hand.

The total time required for testing, including the breaks, was 35 to 40 minutes per patient.

Examiners

Because we were interested in the effect of experience of the examiner on measurement error, we selected 2 examiners with widely differing experience. The first examiner was a 54-year-old male physical therapist (JFvN) with 20 years of experience in testing hand function. The second examiner (JG) was a 22-year-old female medical student with no previous experience with these tests. During a 2-week period, the inexperienced examiner had 5 hours of training by an experienced physical therapist to become familiarised with the equipment and testing protocol. During the training measurements were practised on several subjects without injuries and some patients with hand injuries. We believe that the results obtained by this student are reasonably representative of those that could be obtained by an inexperienced examiner, regardless of whether this is a starting physician or physical therapist, because at this stage they have comparable (i.e., limited) knowledge, attitudes, and skills concerning force measurements

Data Analysis

Statistical analyses were done to determine intraexaminer reliability of data obtained in the 2 sessions performed by the same examiner both for the experienced examiner (Texp1 and Texp2) and the inexperienced examiner (Tinx 1 and Tinx 2) separately. Interexaminer reliability was calculated between the first sessions of the experienced examiner (Texp1) and the inexperienced examiner (Tinx1). Analyses of the measurements of the injured hands (n=33) and noninjured hands (n=33) were conducted separately.

An analysis of variance (ANOVA) was conducted with an SPSS/PC+ program‡ to determine the multiple sources of measurement error. The variance attributed to differences among participants, was

‡ SPSS Inc, 233 S Wacker Dr, Chicago, IL 60606.

designated "Var (P)". The variance attributed to differences between sessions by the same examiner (Texp1 and Texp2, Tinx1 and Tinx2) was designated "Var (S)". The variance ascribed to the different examiners (Texp1 and Tinx1) was designated "Var (T)". Variance due to interaction among participants for intraexaminer sessions was designated "Var (P×S)", and variance due to interaction among participants for interexaminer sessions was designated "Var (P×T)". The interaction components (P×S) and (P×T) were confounded by the residual error. In the intraexaminer analyses, Var (S) and Var (P×S) (i.e., the variance within participants) constituted the error variance. Correspondingly, for the interexaminer analyses, the variance components Var (T) and Var (P×T) constituted the error variance.

From the error variance, the SEM was computed as its square root.[18] Based on the SEM, the SDD with 95% confidence was calculated as $1.96 \times \sqrt{2} \times \text{SEM}$.[24] This SDD can be applied in such a way that only differences between 2 consecutive measurements greater than the SDD can be interpreted with 95% certainty as real change in grip or pinch force. Intraclass correlation coefficients were computed as the ratio of variances among participants (i.e., Var[P]) and the total variance.[16]

Comparing SEMs

In order to test whether differences existed in error variances of different applications of grip and pinch force measurements a test of equality of variances for paired samples was applied. In this analysis, scores between sessions were compared by calculating the correlation coefficient (Pearson *r*) between the sum and difference of the difference scores and testing whether this correlation differed from zero.[17 25 (pp171-172)] In this way, we tested whether differences existed in error variance, and thus SEM and SDD, between the experienced and inexperienced examiners, between measurements of the injured and noninjured hands, and between the 2 handle positions of the grip force measurements and between the 2 pinch force measurements.

Commonly accepted criteria to judge whether the SEM and SDD of measurements are adequate for application of the measurements to individual patients do not exist. Therefore, we compared the SEMs found in our study with those from other studies in which grip and pinch force measurements were investigated. We selected studies from the literature in which values for SEM or SDD were reported and studies from which SEM and SDD can be estimated by using the formulas: $SEM = SD\sqrt{(1 - ICC)}$ [16, 24(p119)] or $SEM = SD_{difference}/\sqrt{2}$,[16(p120)] where SD=standard deviation. These studies included similar groups of patients as in our study (i.e., patients with hand injuries or patients from different groups such as patients with pain, RSD, epicondylitis, and stroke).

Results

Descriptive values (mean and standard deviations) were calculated for all measurements (2 grip and 2 pinch measurements) for the injured and noninjured hands and for the 4 sessions conducted by the experienced and inexperienced examiners (Tab. 1). Evidently noninjured hands have stronger grip and pinch forces. The mean grip force in position 4 was less than in position 2. Key pinch has a considerably greater mean force than tip pinch.

Table 1. Grip and pinch force measurements (in Newtons) obtained by experienced and Inexperienced examiners for both hands of participants with hand Injury of one hand (N=33)

		Experienced Examiner				**Inexperienced**			
		Session 1		Session 2		Session 1		Session 2	
Hand	**Test**[a]	**X**	**SD**	**X**	**SD**	**X**	**SD**	**X**	**SD**
Injured	Grip 2	250	123	253	125	241	122	245	117
	Grip 4	231	110	231	111	231	113	223	109
	Tip pinch	39	17	39	16	37	16	38	16
	Key pinch	63	22	64	22	63	25	62	24
Noninjure	Grip 2	370	116	364	115	345	115	359	118
	Grip 4	326	110	323	108	325	112	317	109
	Tip pinch	55	13	53	12	54	12	54	12

Key pinch	87	18	86	19	86	20	84	20

[a] Grip 2 =measurements of grip force in the second handle position, grip 4 = measurements of grip force in the fourth handle position.

Two scatterplots of measurements obtained for both injured and noninjured hands (n=66) are presented in Figures 2 and 3. Figure 2 shows the measurements of grip force with the second handle position for the 2 sessions conducted by the experienced examiner (Texp1 and Texp2). Figure 3 shows the measurements of the tip pinch force obtained by the 2 different examiners (Texp1 and Tinx1). Both scatterplots demonstrate that there was a high level of correspondence between the 2 sessions and the 2 examiners.

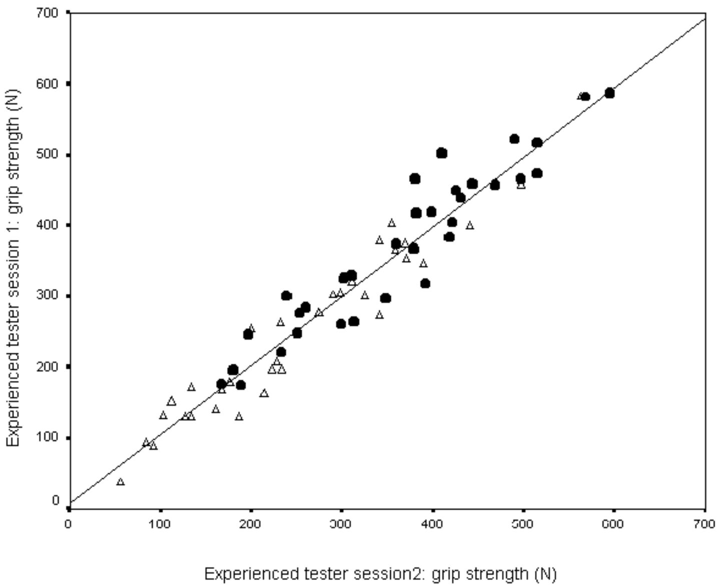

Figure 2. Scatterplot of intraexaminer grip force measurements with the second handle position performed in two sessions by an experienced examiner (Texp1 and Texp2). Δ represents measurements of the injured hands (n=33); ● represents measurements of the noninjured hands (n=33) which are the higher values.

Figure 3; Scatterplot of interexaminer tip pinch force measurements (P1) by an experienced (Texp1) and an inexperienced examiner (Tinx1). Δ represents measurements of the injured hands (n=33); ● represents measurements of the noninjured hands (n=33).

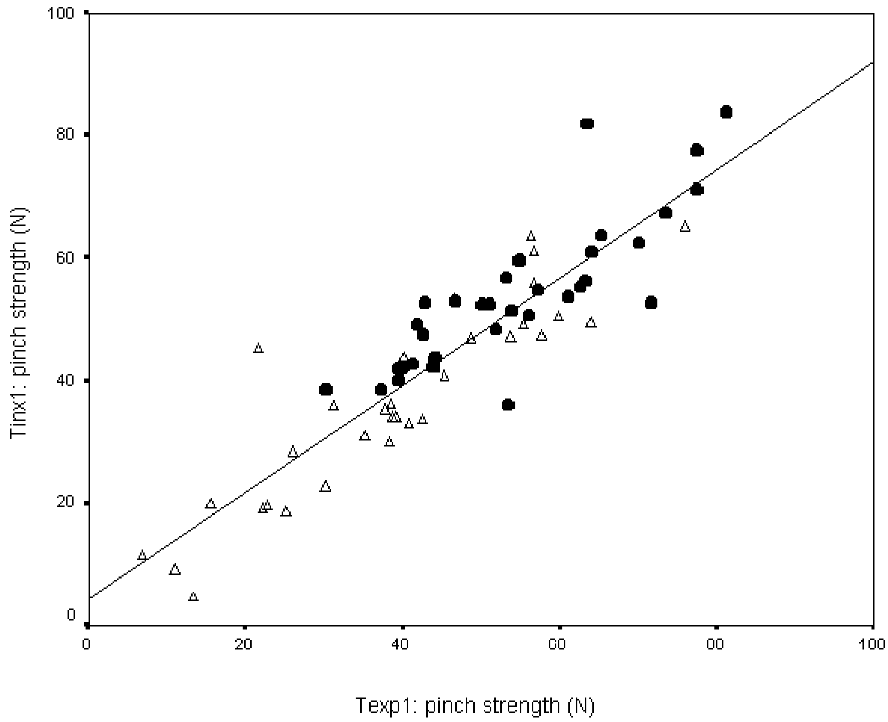

Table 2 presents the results of the ANOVA: the sum of squares, mean of squares, and estimated variance components attributed to different sources. Reliability indexes (i.e., SEM, SDD, and ICC) for the intraexaminer grip and pinch measurements also are presented, ordered by examiner (experienced and inexperienced) and by hand (injured and noninjured). The SEMs ranged from 4 to 29 N, and the corresponding SDDs ranged from 11 to 80 N. The lowest ICC was .82 and the highest ICCs were .97 which, according to the scale suggested by Shrout and Fleiss,[26] should be classified as excellent.

Table 2; For intraexaminer measurements of grip and pinch force (Newton) of injured hands of patients (n=33) by anexperienced and inexperienced examiner, the following data are given: Sum of Squares (SS), Mean Squares (MS) and estimated variance components. For the reliability indexes are given: Standard Error of Measurement (SEM), Smallest Detectable Difference (SDD) and the Intraclass Correlation Coefficient (ICC).

Examiner	Injured / noninjured	Test	Source	SS	MS	Estimated variance	SEM	SDD	ICC
Experienced	Injured	Grip 2	Between patients	972270	30383	14947			
			Within patients	15841	490	490	22	61	0.97
		Grip 4	Between patients	758462	23702	11534			
			Within patients	20257	633	633	25	70	0.95
		Tip pinch	Between patients	16035	501	241			
			Within patients	603	19	18	4	12	0.93
		Key pinch	Between patients	30373	949	483			
			Within patients	510	16	16	4	11	0.97
Inexperienced	Injured	Grip 2	Between patients	899327	28104	13849			
			Within patients	12989	406	402	20	56	0.97
		Grip 4	Between patients	772010	24125	11868			
			Within patients	12443	389	406	20	56	0.97
		Tip pinch	Between patients	15234	476	228			
			Within patients	657	21	21	5	13	0.92
		Key pinch (n=32)	Between patients	36315	1135	547			
			Within patients	1316	41	41	6	18	0.93
Experienced	Noninjured	Grip 2	Between patients	835322	26104	12705			
			Within patients	22198	694	694	26	73	0.95
		Grip 4	Between patients	738201	23069	11114			
			Within patients	26918	841	841	29	80	0.93
		Tip pinch	Between patients	9482	296	140			
			Within patients	539	17	18	4	12	0.89
		Key pinch	Between patients	21601	675	326			
			Within patients	754	24	24	5	13	0.93

Inexperienced	Noninjured	Grip 2	Between patients	822792	26542	12922			
		(n=32)	Within patients	21624	698	698	28	77	0.94
		Grip 4	Between patients	769145	24036	11823			
			Within patients	13478	408	408	20	56	0.97
		Tip pinch	Between patients	8858	277	124			
			Within patients	892	28	28	5	15	0.82
		Key pinch	Between patients	23848	745	351			
			Within patients	1383	43	43	7	18	0.89

Grip 2 are measurements of grip force in the 2^{nd} handle position, ** Grip 4 are measurements in the 4^{th} handle position

The interexaminer data are presented in Table 3 and show comparable values.

Table 3. Interexaminer application of grip and pinch force measurements (Newton) of injured and noninjured hands of patients (n=33). Sum of Squares (SS), mean Squares (MS) and estimated variance are presented, as well as the reliability indexes: Standard Error of Measurements (SEM), Smallest Detectable Difference (SDD) and the Intraclass Correlation Coefficient (ICC).

		Source	SS	MS	Estimated variance	SEM	SDD	ICC
Injured hands	Grip 2	Between patients	948096	29628	14584			
		Within patients	16279	493	493	22	62	0.97
	Grip 4	Between patients	763813	23869	11508			
		Within patients	27279	852	852	29	81	0.93
	Tip pinch	Between patients	15805	494	234			
		Within patients	855	28	29	5	15	0.89
	Key pinch	Between patients	33541	1048	509			
	(n=32)	Within patients	955	30	30	5	15	0.94
Noninjured hands	Grip 2	Between patients	835379	26106	12899			
		Within patients	35320	1104	1111	33	92	0.92
	Grip 4	Between patients	774343	24198	11857			
		Within patients	15495	484	484	22	61	0.96
	Tip pinch	Between patients	9579	299	136			
		Within patients	857	27	27	5	14	0.84
	Key pinch	Between patients	21771	680	315			
		Within patients	1594	49	50	7	20	0.86

No differences were found in the error variances of grip and pinch force measurements between injured and noninjured hands or performed by experienced and inexperienced examiners. Similarly, no differences were found in the error variances of the measurements between the 2 handle positions of grip force or between the 2 pinch techniques.

Tables 4 and 5 present comparisons among studies investigating grip and pinch force measurements, including the type of dynamometer used, characteristics of the subjects, means and standard deviations of force measurements, and reliability indexes (i.e., SEM, SDD, and ICC). The measurement errors of the SEMs of grip force measurements are comparable in most of the studies, except for those of Nitschke et al[10] and Smidt et al,[12 13] in which relatively low values were found (Tab. 4). For pinch force measurements, the SEMs were 4 or 5 N, with the exception of the higher values of 11 N found by Geertzen et al[11] (Tab. 5).

Table 4. Comparison of intratester measurements from six grip force studies with data from the current study. Type of dynamometer, subjects, mean, standard deviation (SD), SEM and SDD are compared.

Study	Handheld Dynamometer	Subjects		n	Mean (N)	SD (N)	SEM (N)	SDD (N)
Spijkerman et al.[6]	Prototype Lode	Healthy		16	231	18	*14*	*39*
		Hand injuries		8	434	10	*25*	*59*
Brown et al.[7]	Dexter grip	Hand injuries		30	267	115	*30*	*84*
Nitschke et al.[10]	Jamar	Healthy women		32	325	69	*20*	*57*
		Women with NSRP		10	174	62	*18*	*59*
Geertzen et al.[11]	Citec grip	RSD	Unaffected hand	29	123	66	*24*	*66*
			Affected		84	51	*25*	*71*
Smidt et al.[12]	Jamar	Epicondylitis	Uninvolved	50	340	100	*13*	*37**
			Involved		300	110	*14*	*39**
Boissy et al.[13]	Lafayette grip	Healthy		10	382	87	*33*	*92*
		Stroke		15	130	84	*25*	*69*
Present study	Lode grip handle pos. 2	Hand injuries	Noninjured	33	367	115	26	73
			Injured		252	123	22	61
	Lode grip handle pos. 4		Noninjured		324	109	29	80
			Injured		231	109	25	70

Abbreviations: n = number of subjects; NSRP = non-specific Regional Pain syndrome; RSD = Reflex Sympathetic Dystrophy; SEM = Standard Error of Measurement; SDD = Smallest Detectable Difference;

All data converted to Newton (Nitschke, Geertzen and Smidt data were in kgf: and multiplied by 10 to Newtons; Brown et al.'s within patients data were in pounds and multiplied by 4.448). Data are from intratester measurements except Geertzen et al. and Smidt et al. gave intertester data. Data from Brown et al. are the mean of three testers.

Figures in Italics are estimated from ICC values presented in the studies.

* Figures from Smidt et al. are estimated from the SD_{diff} presented in their study. These values of the SDD differ from the values in the paper of Smidt, who submitted an erratum on this point.

Table 5. Comparison of data from earlier pinch force measurement studies with data from the current study. Type of dynamometer, subjects, unit of measurement, mean, standard deviation, SEM and SDD are compared. All data in Newtons.

Study	Handheld Dyna-mometer	Subjects			n	Tester	Mean (N)	SD (N)	SEM (N)	SDD (N)	ICC
Geertzen et al. [9]	Citec	RSD	Unaffected side	Key pinch	29	inter	67	19	11	30	*
			Affected side				56	23	11	31	*
Brown et al.[12]	Dexter	Hand injuries		Tip pinch	30	Intra (mean of 3)	48	18.2	4	7.1	0.96
				Jaw pinch			64	22.7	4	8.5	0.96
Present study	Lode	Hand injuries	Noninjured	Tip pinch	33	intra	53	11.7	4	12	0.89
			Injured				39	15.6	4	12	0.93
	Lode		Noninjured	Key pinch			86	19	5	14	0.93
			Injured				64	22.4	4	11	0.97

n= number of subjects; SEM = Standard Error of Measurement; SDD = Smallest Detectable Difference; ICC = Intraclass Correlation Coefficient; RSD= Reflex Sympathetic Dystrophy. * no data available

Discussion

In our study, high ICCs were found for the reliability of grip and pinch force measurements in subjects with hand injuries. In our view, however, a high ICC should not be interpreted as a small measurement error because, in an ICC, measurement error and real variability between subjects are expressed in relative terms. Expressing the reliability as a dimensionless ratio of variances does not allow us to interpret the reliability in terms of an individual score. To decide whether a person’s grip force has changed after a period of rehabilitation, a physical therapist must know which part of the change measured was real and which part is due to measurement error. To accomplish this, we calculated the SEM and SDD.

In our study, the SDD of the grip force measurements (second handle position of the injured hands was 61 N for measurements obtained by the experienced examiner (Tab. 2). This finding means that for grip force measurements taken by the experienced examiner (Texp), a change in force of at least 61 N is needed between 2 sessions to be 95% confident that a real change has occurred. The 2 different types of pinch force measurements (tip pinch and key pinch) showed a much smaller SDD; for the experienced examiner, the SDDs for the injured hands were 11 to 12 N (Tab. 2).

In the case of our 2 examiners with widely differing experience, comparison of the SEMs showed no differences between them. Thus, for grip and pinch force measurements, it appears that a brief training period was sufficient for an inexperienced examiner to reach a level of reliability comparable to that of an experienced examiner. Given the small number of examiners in our study, however, this cannot be stated with certainty.

More examiners, however, would entail a longer measurement time, which might fatigue the patient or decrease his or her concentration, both of which may influence the measurement error. We attempted to compensate for the small number of examiners by selecting 2 examiners with what we considered maximally different experience. Given that no differences in measurement error between the 2 examiners were found, we contend that having more examiners (e.g., with intermediate levels of experience) obtain the measurements would not have affected our conclusions. Although we do not have data to support this view, we believe it is a reasonable interpretation.

Other factors also may influence the measurement error. For example, we also examined the difference in SEMs between grip and pinch force measurements of the injured and noninjured hands. The measurement error, however, did not differ between the injured and noninjured hands. No differences were found between the SEMs of grip force measurements in the 2 handle positions or between both types of pinch force measurements. Therefore, for applications in clinical practice, we contend one SEM value can be applied for grip force measurements for both handle positions and one SEM value can be applied for pinch force measurements, irrespective of injury and experience of the examiner.

Accepted criteria to judge the SDD of grip and pinch force measurements do not exist. Therefore, we compared our findings with those of 6 studies in which grip and pinch force measurements were investigated in similar and different patient categories (i.e., patients with hand injuries,[6] women with NSRP,[10] patients with RSD,[11] patients with epicondylitis,[12] and patients after a stroke[14]) (Tab. 4). The SEMs of grip force measurements in these different studies are comparable. However, the differences in means and ranges of the measured force levels in these studies are remarkable (e.g., the mean grip forces in the affected hands ranged from 84 to 300 N). To determine the value of a particular measurement in a population during clinical practice, we believe it is essential to know in which range the changes of muscle force take place. For example, in people with hand injury, the grip force will be lower shortly after the trauma. During later phases of rehabilitation, the increased muscle force generally reaches a plateau after many months. If the difference in the grip force between the start and end of the rehabilitation is, for example, 100 N, an SDD of 80 N will mean the measurement is inadequate to detect changes. If the range in which the forces change is as wide as 300 N, an SDD of 30 N is certainly sufficient to detect changes during the rehabilitation process. In this latter example, a virtual scale of 10 steps is achieved.

To determine whether the calculated measurement error is small enough to make a test valuable in clinical practice, different methods have been applied in the studies we cite. Geertzen et al [11] concluded that the SDD is too large in relation to the mean force measured to be useful in patients with RSD. Smidt et al[12] suggested that an SDD less than 10% of the total range of the measurements would be acceptable.[13] The range, however, is determined by the extreme values of the measurement, whereas the standard deviation is less influenced by the extreme values. In our study, therefore, we re-examined the SDD in relation to the standard deviation of the measurements by calculating the SDD/standard deviation ratios. The SDD/standard deviation ratios were 0.5 to 0.6 for grip force measurements using the second handle position and 0.6 to 0.7 when using the fourth handle position. These findings mean that 6 to 7 steps of changes in force level can be detected within the 95% distribution ("virtual scale") of impaired to normal levels of grip force. In our opinion, this SDD/standard deviation ratio is useful in order to gain better insight as to whether measurements can be used to detect clinical meaningful changes. A more definitive conclusion concerning the usefulness of the measurements can be made by relating the SDD relative to the magnitude of changes in force measurements in a prospective study of patients throughout the entire rehabilitation process.

Conclusions

According to the ICC values obtained in our study, the reliability of grip and pinch force measurements is excellent. However, assessment of the measurement error and detectable change in muscle force between 2 consecutive measurements demonstrated that, in grip and pinch force measurements in individual patients, only relatively large changes can be adequately detected.

Measurement error did not differ between the experienced and inexperienced examiners or the injured and noninjured hands. Similarly, no differences were found in the grip force measurements for the 2 handle positions or in the tip pinch and key pinch force measurements. Further study of the SDD/standard deviation ratio is needed to develop clear criteria to judge whether measurement error is acceptable to detect changes in individual patients. The limited number of examiners and the use of subjects who were pain-free should be considered when applying our results. Further study of the

SDD/standard deviation ratio is needed to develop clear criteria to judge whether measurement error is acceptable to detect changes in individual patients.

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CHAPTER 6

The Rotterdam Intrinsic Hand Myometer (RIHM) *A technical note*

Thoughts are mightier than strength of hand

Sophocles (496-406 BC)

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Abstract

The Rotterdam Intrinsic Hand Myometer (RIHM) is designed to measure the forces of the intrinsic hand muscles for research and clinical purposes. Earlier attempts to measure these muscle forces were with devices designed to measure the abduction force of the thumb, some were hand-held, or mounted on a jig or standard and could not measure the opposition of the thumb. All such instruments made measurements by pushing on the digit, increasing the risk to produce forces not perpendicular to the digits. Our device is a hand-held dynamometer that uses a pulling method and has novel technical features which improved reliability.

Introduction

In the assessment of the muscle forces of the intrinsic muscles of the hand there is a need for specific measurements of these muscles in isolation. Dynamometers are available that measure grip strength and pinch strength of the hand [1-4], but few dynamometers have the possibility to measure the intrinsic muscles of the hand separately.[5-8] Knowledge on the specific force of the intrinsic muscles will provide important information for developing, for example, new methods to repair peripheral nerves of the hand, new therapies aimed at strengthening the intrinsic muscles of the hand, and bio-mechanical analyses of muscles forces of the lumbricals and interossei muscles in the clinical situation.

A previous study tested the reliability of measurements made with a generic industrially designed hand-held dynamometer (AIKOH) to assess the force of several of the intrinsic muscles of the hand. It was found that only relatively large changes in intrinsic muscle force could be detected [9]. Another disadvantage was that, for the median nerve innervated muscles of the thumb, only one muscle could be measured i.e. the Abductor Pollicis Brevis (APB), while several ulnar nerve innervated muscles could be measured. Measuring the APB with sufficient isolation from the other thenar muscles providing abduction to the thumb is difficult. The possibility to measure another muscle innervated by the median nerve, i.e. the Opponens Pollicis (OP), would be valuable.

The aim of this study was to develop an instrument with specific requirements: i.e. improved reliability to measure the muscle force of the intrinsic muscles, hand-held and portable, possibility to measure the OP force of the thumb, ergonomically designed grip, appropriate visual feedback of line of pull, and minimal errors from off-axis loading thus allowing measurement of axial forces only.

Design

Design of dynamometer

The new Rotterdam Intrinsic Hand Myometer (RIHM) (Fig. 1) is made of a strong lightweight plastic (PED) which contains the battery, the force sensor and the electronics. The peak forces can be read from a digital display on top of the device. The grip is positioned at a 97° angle to the horizontal, allowing the tester to hold the wrist in a stable, neutral position.

Figure 1. Photograph showing the force measurements of the abductor muscles of the little finger with the dynamometer. The leather band is placed around the little finger.

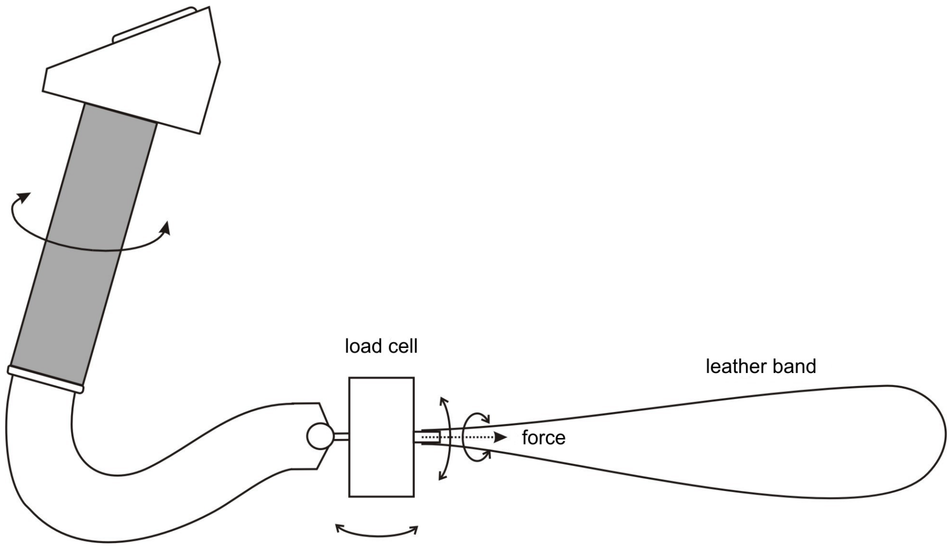
An important difference compared with other instruments is the pulling technique of the RIHM, whereby the forces are measured by pulling on a leather band placed on the digit. Placing a band around the thumb allows measuring the forces of the OP muscle.

From the tester’s viewpoint pulling towards their own body with their upper arm supported against the side of the thorax enables better control than pushing. For practical reasons (e.g. hand size) a 15-cm long leather band is used; this length allows the angle of deviation angle to be easier observed.
To further decrease any erroneous forces introduced by the tester, a small cylindrical part is connected to the handgrip of the instrument by means of a ball joint, and contains the button load cell (type BC301 from DS Europe). This construction, together with a rotating handgrip, ensures loading perpendicular to the load cell (Fig. 2). This prevents the examiner from introducing torques in the horizontal and vertical planes, as well as rotation around the line of work and rotation of the band around the finger.

Electronic circuit

The handgrip of the device houses the rechargeable battery, the curved part houses the printed circuit, and the display unit with control buttons is on top of the device. A programmable LCD digital panel meter (LASCAR type SM1) displays the maximal reading. This microcontroller-based module is designed around an alphanumeric LCD. The LED back light display shows the 4.5 digit voltmeter readings as well as a comprehensive operator menu. The user can select the desired range, decimal place, as well as calibration settings. Because all set-ups, including calibration, are performed via software, there are no user adjustable potentiometers. The module stores all settings when the power is switched off. The unit is powered by the internal 9-volt rechargeable NiMHy battery or an external plug in a power adapter; when connected to this adapter the battery will be charged automatically. To save power, the device automatically switches off every few minutes.

Figure 2 Drawing of the Rotterdam Intrinsic Hand Myometer (RIHM)



A diagram of the electronic circuit (Fig. 3) shows the strain gauge bridge of the load cell (left-hand side): the bridge signal is amplified by the differential amplifier 1, and amplifier 2 performs lowpass filtering and level shifting. The force curve signal is available on the force output connector connected to this amplifier. The force curve signal is connected to a peak detector with a fast peak response of < 10 msec.

Figure 3 Diagram of the electronic circuit of the RIHM

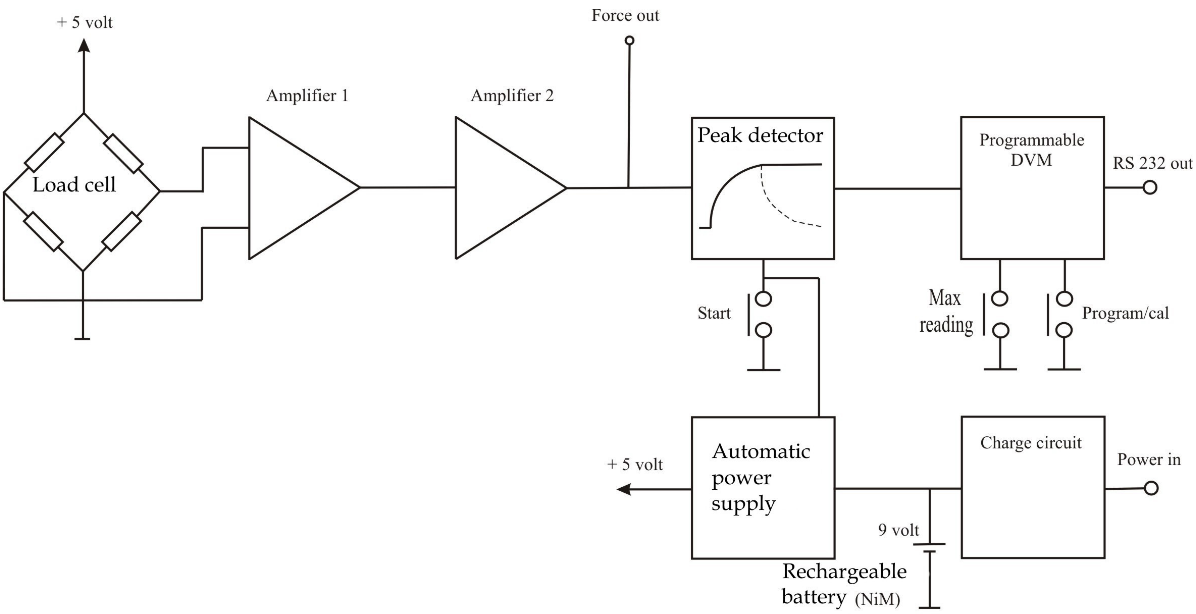


Diagram of the electronic circuit

Clinical experience

Reliability of the RIHM has been studied in patients with peripheral nerve injuries and was found to have smaller measurement error compared with the AIKOH measurements.[10] In clinical use the measurements have provided important data showing that the conventionally used grip and pinch strength dynamometers do not adequately reflect recovery of the intrinsic muscles.[11]

We conclude that the RIHM is an easy to use (hand-held) instrument providing reliable measurements of the intrinsic muscles of the hand.

Acknowledgement

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CHAPTER 7

Analysis of the application of force measurements of the hand: a comparison of two hand-held dynamometers

The hand is an important functioning organ requiring rest and performing the greatest part of activities, including locomotion, if need be. Through the hand, as through sight and hearing, we form a conception of the outside world. It is truly the extension of our brain into the surrounding world;
it is the mirror of our innermost response to the outside world.

Emanuel B Kaplan.
Functional and Surgical Anatomy of the Hand (1965)

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Summary

Objective. To assess the accuracy of measurement performance of two hand-held dynamometers in the application of force measurements of the intrinsic muscles of the hand.

Design. Repeated measurements with a generic dynamometer (AIKOH) using a pushing technique and with a newly designed instrument, the Rotterdam Intrinsic Hand Myometer (RIHM) using a pulling technique.

Methods. Three force measurements were studied of the right hand of ten healthy persons: little finger abduction, index finger abduction and thumb palmar abduction. The position and angle of application was recorded with a three-dimensional videorecording technique. Three repeated measurements within a session were averaged to determine the systematic differences and variances of the measurements of the two dynamometers

Results. The variance was smaller for all three measurements of the RIHM regarding the positioning of application and the angle of application of the index finger abduction in the frontal plane. Systematic differences between the dynamometers were found only for the angle of application in the frontal plane of index finger and thumb measurements in favour of the RIHM.

Conclusion. Performance of force measurements of the intrinsic muscles of the hand with the RIHM dynamometer had less variances than the AIKOH dynamometer in the positioning of the instruments at the same anatomical reference point of the finger. The difference in angle of application has much smaller influence on the variance of measurements between the two instruments.

Relevance. Instruments for force measurements of the hand are important in evaluating the hand function. A new force measuring instrument, the Rotterdam

Intrinsic Hand Myometer (RIHM), has been developed with a pulling technique to improve reliability. Because small inaccuracies in applying a dynamometer may have considerable consequences for measurement error, determining the cause of measurement error will provide information on how to improve measurement instruments.

Introduction

Weakness in muscle force resulting from neurological or musculoskeletal lesions can greatly reduce the patient's hand function and often cause major impairments and disabilities. Measurements of the muscle force of the hand through objective and reliable methods are important in order to follow the recovery rate and effectiveness of treatments after upper extremity nerve injuries [1-3], or changes of muscle force in several hereditary motor and sensory neuropathies.[4 5] Different methods for monitoring hand function have been investigated by many researchers who work in the area of hand rehabilitation.[6-11]

Measurement of muscle force is possible by non-instrumental techniques such as manual muscle strength testing (MMST), or instrumental techniques such as grip and pinch force dynamometers[12] and electro-physiological methods. Mannerfelt was one of the first to measure the intrinsic muscle force of the hand with a dynamometer.[13] Later, others have designed devices for e.g. force measurements of the index finger [14-16] and intrinsic thenar muscles of the thumb.[17-19]

In a previous study we assessed the reliability of force measurements of the intrinsic muscles of the hand with a generic industrially designed hand-held dynamometer using the pushing technique (AIKOH) in 24 patients with ulnar and/or median nerve injury.[20] The Standard Error of Measurements (SEM) for the little finger, index finger and thumb abduction were 10, 11 and 12 N, respectively.[20] We concluded that only relatively large changes in intrinsic muscle force could be confidently detected. With a specifically designed dynamometer (RIHM), using a pulling technique (Fig. 1), similar muscle strength measurements in 27 patients with ulnar and/or median nerve injuries showed much lower SEMs of 2.2, 2.3, 5.8 N, respectively.[21]

We hypothesised that this reduction of measurement error was mainly due to better standardisation of these measurements due to an improved consistency of application of the dynamometer at the right position and the right angle during testing. The dynamometer is usually placed at a joint crease because it is easy to identify. Positioning of the dynamometer needs to be done consistently at precisely the same position (Fig. 2); e.g. when the muscles around the metacarpophalangeal (MCP) joint can deliver a net moment of 25 Nm, the force that is measured at a position (arm) of 5 cm to the joint (X in Figure 1), will be 5 N (force = moment/arm). However, when the dynamometer is positioned 0.05 m (Z) more proximally from that point, making the arm 0.045 m from the MCP joint, the force will be 2.5/0.045 = 5.5 N, i.e. about 10% higher than in case of accurate placement.

Regarding the angle of application, an accurate measurement is performed when the dynamometer is positioned perpendicular to the finger and thumb in two directions; in the frontal plane of the hand (dividing the hand into an anterior and posterior portion) and the transverse plane (dividing the hand into a distal and proximal halve). A change in the angle between the device and the finger may cause large differences in outcome force. For example, applying the dynamometer at an angle of 25‘ will cause an underestimation of the measured force of almost 10% (cosinus 25‘ = 0.91).

Thus, relatively small changes in the position and angle when applying the dynamometer may have considerable consequences for measurement error. The aim of this study was to compare the accuracy of the older industrial dynamometer (AIKOH) with a newly designed instrument, the Rotterdam Intrinsic Hand Myometer (RIHM)[22] , in positioning the instruments at exactly the same point of the finger and applying it at the correct angle to the digit in the two planes.

Both the angle and position of application were determined with a three-dimensional (3D) videorecording technique.[23-25] Measurements with the two instruments were compared with respect to the consistency and variance of positioning and angle of force application during testing.

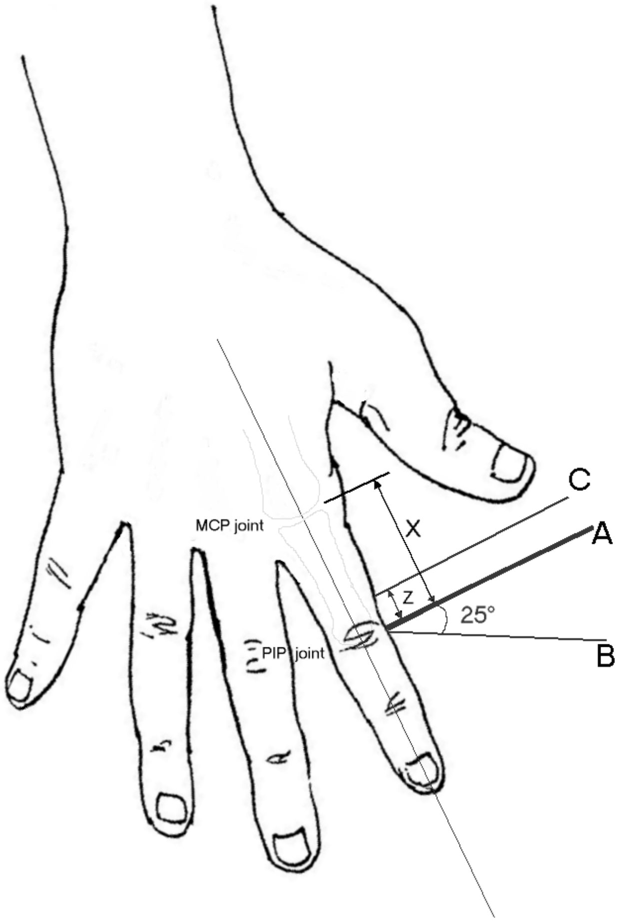


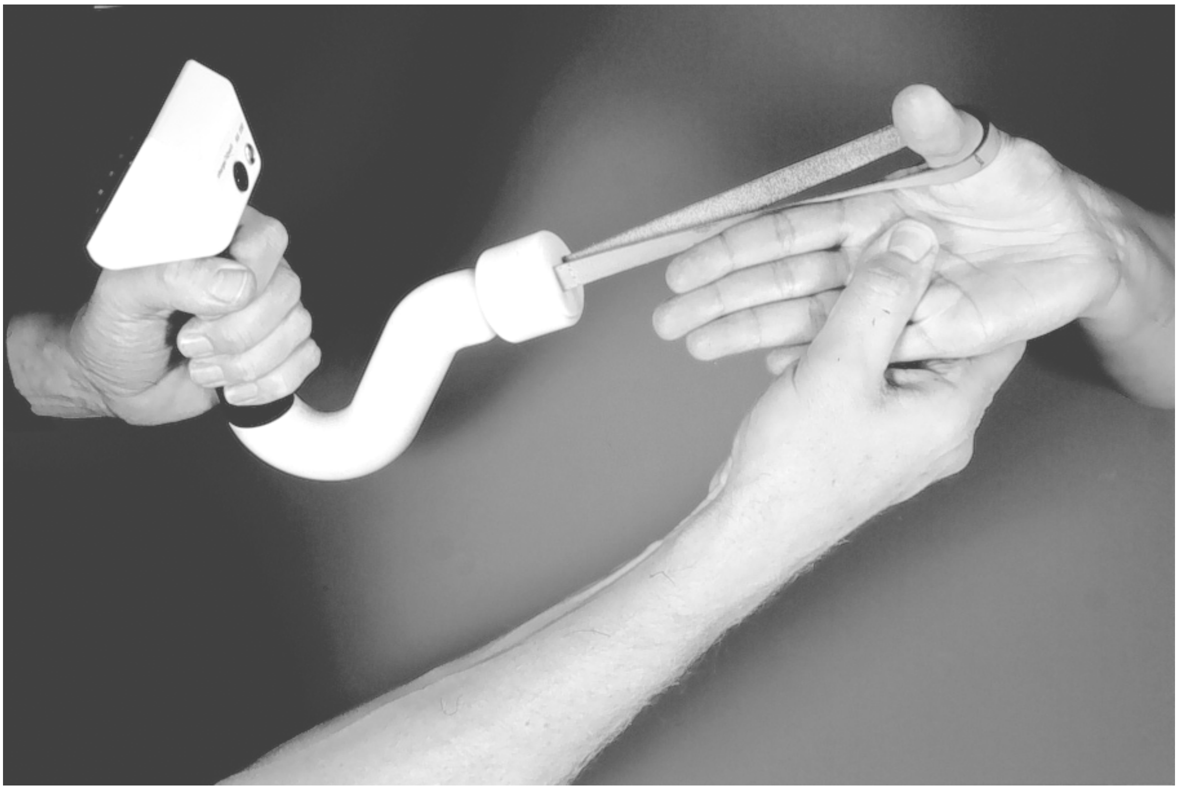
Figure 1. Measuring the abduction force of the little finger. A = measuring the force at the PIP joint, with the right distance X (arm) from the MCP joint, and perpendicular to the finger in both planes (= 90‘); B= when the dynamometer is erroneously held at a 25‘ angle; C= when the dynamometer is erroneously held at a distance Z from the correct point at the PIP joint.

Material and Methods

Test Protocol

The right hand of 10 healthy persons was tested. These were 5 males and 5 females with a mean age of 31.5 (SD 7,1) years. Three force measurements were analysed: little finger abduction, index finger abduction and thumb palmar abduction (Fig. 2).

Figure 2. Force measurement of the abduction of the thumb with the RIHM dynamometer .



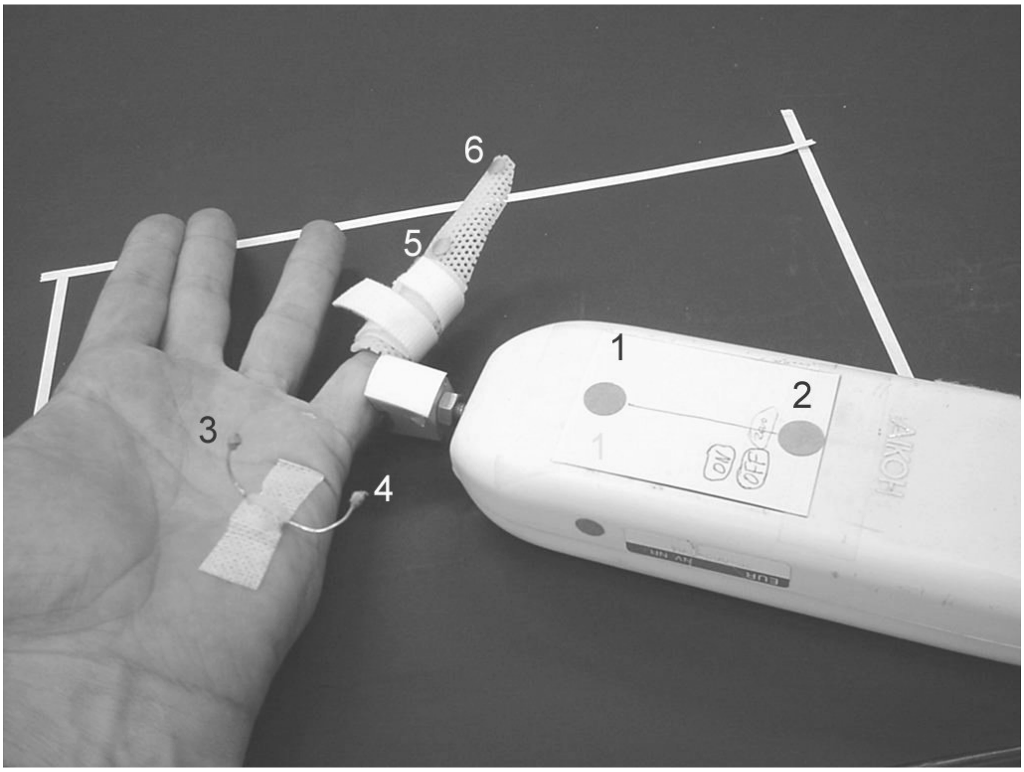
The first two movements are produced by ulnar nerve innervated muscles and the latter is a movement produced by the thenar muscles of the thumb, which is mainly a median nerve
innervated function. For little finger abduction the resistance force was applied at the ulnar side of the proximal interphalangeal (PIP) joint crease of the little finger. For the index finger abduction, the anatomical reference point was chosen at the radial side of the PIP joint and for the thumb movement this was the radial side of the MCP joint crease. Hand position, fixation and anatomical reference point for the application of resistance force were comparable to the MMST technique.[26]

The volunteer and examiner were seated at a table opposite each other. Participants were instructed how to hold the finger/thumb in the maximally abducted position and were told to maintain the finger in that position, while the examiner pushed or pulled the finger in the opposite direction with the dynamometer. An experienced tester familiar with both instruments (TARS) completed all the measurements.

This study employed two hand-held instruments: the generic AIKOH dynamometer (Aikoh Model 9520A.B. Aikoh Engineering Co., Ltd. Tokyo, Japan) using a push technique, and the specifically designed RIHM dynamometer (Experimental Medical Instruments department of the Erasmus MC, Rotterdam, the Netherlands) with a pull technique. Three measurements, comprising one session, were performed, then the dynamometer was removed and the person asked to move the hand out of the testing position. The dynamometer was positioned again at the same anatomical reference point and another session of three measurements was carried out. This was repeated one more time, providing three sessions of three measurements per movement. Both the order of the measurements (i.e. testing the little finger, index finger and thumb) and the order of the testing with the two instruments were randomised.

In order to obtain 3D position measurements, two videocameras were used to record the signals from reflective markers on the hand and dynamometers. These markers reflected the infrared light sent from a light source attached to the camera. Three pairs of infrared light reflecting markers were used (Fig. 3). For the AIKOH one pair (no.1 and 2) was on the dynamometer and for the RIHM the markers were on the pull string. A small bar with two markers (no. 3 and 4) was taped on the skin above the metacarpal bone such that these two markers were parallel to the plane of the hand. The third pair (no. 5 and 6) was located on a small splint which was attached with two Velcro straps to the distal phalanx of the finger.

Figure 3. Force measurement of the abduction of the little finger with the AIKOH dynamometer. Reflective markers no. 1 and 2 on the dynamometer, no. 3 and 4 on a small bar which was taped on the skin above the metacarpal bone, no. 5 and 6 were fixed on a small splint, attached with two Velcro straps to the distal phalanx of the finger.



The markers were illuminated by an infrared light source mounted on the cameras. The image co-ordinates from the two cameras were combined to 3D spatial co-ordinates using Direct Linear Transformation.[23] The video signal was digitised using a Vision Dynamics[1] VCS 512 videoprocessing board to calculate the marker co-ordinates. From previous tests, the resolution of the system proved to be about 0.1 mm.[24]

Data processing

To record the point of application of the dynamometer, the position was determined by measuring the distance between one marker on the small splint at the fingertip (no. 5) and a virtual line through the two markers on the dynamometer (no. 1 and 2), which provided the position in millimetres (mm). Systematic difference was not

[1] Hemel Hempstead, UK

relevant because the position of markers 3 and 4 was chosen at a point which gave the least movement; proximal of the MCP joint. The exact moment arm between the MCP joint and the position of application at the IP joint could therefore not be established. Regarding the angle of application of the dynamometer, a perfect measurement would provide two 90‘ angles, recorded as a zero degree difference in angle in both the frontal and transverse plane of the hand. Systematic differences could be calculated for angle measurements.

For the nine measurements, mean and SD were calculated. Mean differences in position (mm) and angles (degrees) of application between both instruments were calculated. To test whether differences exist between both instruments regarding the variance of position and angle of force applications between sessions, a repeated measurements analysis was carried out using Proc Mixed of the Statistical Analysis System (SAS version 8.2 of the SAS Institute Inc., Cary, NC, USA). Three repeated measurements within a session were averaged, and the analysis was done on the three session averages. In the statistical models, person was a random factor and instrument was a fixed factor. For each outcome, two models were fitted. The first model assumed that the between sessions variance was equal for both instruments, the second model allowed that the variances were different. The likelihood ratio test comparing these models was used to test the null hypothesis that the between sessions variance of the two instruments was identical.

Results

Table 1 presents data (mean, SD) on the position (mm) at which the two dynamometers (AIKOH and RIHM) were placed for measurement of the little finger, index finger and thumb abduction. There was a significant difference between the two instruments for the thumb abduction and little finger abduction measurements. The variance between three sessions of positioning the dynamometer was smaller ($p < 0.0001$) for all three finger measurements with the RIHM as compared to the AIKOH measurements.
Table 1 also presents data (mean, SD) on the angles, i.e. deviations from 0‘, recorded in two planes (frontal and transverse) with both dynamometers. In the frontal plane the mean of the angle measurements of the RIHM dynamometer was smaller (closer to 0‘) for the index finger and thumb measurements as compared to

the mean of the angles measured with the AIKOH dynamometer.

The variances of the angles between three sessions with the AIKOH and RIHM dynamometers are also presented. In the frontal plane the variances of the RIHM measurements were smaller only for measurement of the index finger. In the transverse plane, no differences in variance of the angles between sessions with the AIKOH and RIHM measurements were found, although we did find a trend that the variance of the little finger measurements was smaller for measurements with the RIHM (p = 0.11).

Table 1. Data on position and angles recorded with two dynamometers; a generic (AIKOH) and newly designed Rotterdam Intrinsic Hand Myometer (RIHM). Position is the distance between the line through markers 3 and 4, and the place where the dynamometer is positioned (mm). Angle measurements are in two planes (frontal and transverse) with results in degrees (˚) of difference from 90˚ application. For both dynamometers, mean, SD and mean differences of nine measurements are presented and the between session variance of three sessions. In the last column the variance between three sessions of the two dynamometers is presented.

			AIKOH		RIHM			Between session Variance		
Plane			Mean	SD	Mean	SD	Mean Differ.	AIKOH	RIHM	*P*
Position (mm)		Little finger	87.0	5.7	91.9	1.1	4.9*	6.0	0.81	<0.0001
		Index finger	58.5	8.0	56.7	2.3	1.8	61.9	0.54	<0.0001
		Thumb	65.2	9.7	54.5	3.6	10.7*	29.1	1.82	<0.0001
Angle (˚)	Frontal	Little finger	7.9	3.9	6.5	4.4	1.4	5.7	4.7	0.75
		Index finger	7.5	7.0	3.3	2.2	4.2*	19.0	2.7	0.0001
		Thumb	13.5	5.8	7.6	6.8	5.9*	19.8	13.0	0.44
	Transverse	Little finger	12.9	9.7	12.0	9.9	0.9	21.2	10.1	0.11
		Index finger	16.8	10.2	16.1	9.6	0.7	13.3	10.2	0.58
		Thumb	13.2	12.1	9.0	6.3	4.2	29.6	19.0	0.44

* Significant difference (p> 0.05) between AIKOH and RIHM

Discussion

In many muscle force measurements with dynamometers, the instrument is pushed against the body while the patient tries to resist the movement, e.g. the microFET [27], Citec [28], Nicholas CANDHY [29] and Kin-Com.[30] In our previous study on force measurements of the intrinsic muscles of the hand with the AIKOH, a similar pushing method was used. In an attempt to decrease the measurement error, we questioned whether the reliability could be improved by using a pulling technique, which may allow for a better visual standardisation of measurement performance.

In our previous studies on the intraobserver reliability of the forces measured with the AIKOH and the RIHM dynamometers, in a comparable group of patients with injuries to the ulnar and median nerve the Standard Error of Measurements (SEM) were much lower for the RIHM measurements.[21] We hypothesised that this reduction in measurement error might be due to better standardisation of these measurements with the RIHM dynamometer due to the improved consistency of the application of the dynamometer at the right position and the right angle during testing.

The present study analysed the control of the point and angle of application of the older (pushing technique) and the new dynamometer with the pulling technique. Differences between the two instruments were found, especially in the position of application. We found that the pulling technique with the RIHM showed systematic differences for two measurements, while the variances between three sessions was smaller for all three measurements of the RIHM dynamometer. Apparently the point at which the dynamometer is placed is an important source of measurements error. Standardisation of this aspect might be even further improved by e.g. drawing of a small line on the finger/thumb.

In the angle of application the main differences were found between the AIKOH and RIHM in the frontal plane measurements. This might be due to the fact that the finger will move in this plane during testing. This knowledge is useful in training examiners in a standardised performance of the measurements and thus might improve the reliability and standardisation of measurement protocols.

Besides the method of application of resistance force by pulling (RIHM) or by pushing (AIKOH), there are other factors which could affect the measurement error. For example, differences in the size and shape of the grip between both dynamometers and the position of the arm of tester might also influence the measurement error. Since the RIHM could be held closer to the body of the tester, less strength was needed to control the dynamometer.

The described video technique provided a method to accurately quantify how the application of the two dynamometers compared while applying a force to the hand. Application of the splint with the two markers was straightforward, but placement of the small bar with the markers 3 and 4 was more difficult and some minor movements where inevitable due to movements caused by the muscles and tendons just beneath the skin were the marker was placed. However, the same marker placement was used for measurements of both instruments, therefore any error would have had the same systematic inaccuracy for both dynamometers.

One limitation of this study is that the same experienced tester performed all measurements. The difference in variances between the two instruments might have been less obvious when performed by a person without experience. The results of this study may help an inexperienced tester to quicker learn how to perform adequate and reliable tests.

In conclusion, we found less variation between sessions in positioning of the dynamometer in measuring muscle force and a smaller systematic error in the frontal plane. The performance of several force measurements of the intrinsic muscles of the hand with the newly designed RIHM dynamometer was more accurate and less variable than with the AIKOH dynamometer, especially in positioning the instrument at the same reference point of the finger. The difference in angle of application has a much smaller influence on the variance of measurements between the two instruments.

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CHAPTER 8

Measuring the Strength of the Intrinsic Muscles of the Hand in Patients with Ulnar and Median Nerve Injuries; Reliability of the Rotterdam Intrinsic Hand Myometer (RIHM)

The human hand is so beautifully formed, it has so fine a sensibility, that sensibility governs its motions so correctly, every effort of the will is answered so instantly, as if the hand itself were the seat of the will; its action are so powerful, so free, and yet so delicate, as if it possessed quality of instinct in itself, that there is no thought of its complexity as an instrument, or of the relations which make it subservient to the mind.

Charles Bell (1774-1842)
The Hand - Its Mechanism and Vital Endowments as Evincing Design (1833)

Reprinted from *Journal of Hand Surgery (Am)*, Vol 29A. Schreuders TAR, Roebroeck ME, Jaquet J-B, Hovius SER, Stam HJ. Measuring the strength of the intrinsic muscles of the hand in patients with ulnar and median nerve injury; reliability of the Rotterdam Intrinsic Hand Myometer (RIHM). p 318-324, 2004. With permission from American Society for Surgery of the Hand.

Abstract

The aim of this study was to determine the reliability and measurement error of measurements of the intrinsic muscle strength of a new hand-held dynamometer (the Rotterdam Intrinsic Hand Myometer; RIHM).

With the RIHM we obtained repeated measurements of the intrinsic muscle strength of the hand in 27 patients with peripheral nerve injury of the ulnar and/or median nerve in different stages of their rehabilitation. The average time period after injury was 4.4 years (range 99 days - 11 years).

Results show that the Intraclass Correlation Coefficients (ICC's) were higher than 0.93. For the two ulnar nerve innervated movements the Standard Error of Measurements (SEMs) were: 2.2 and 2.3 N, and the Smallest Detectable Differences (SDDs) were 6.1 and 6.3 N, respectively. For the two median nerve innervated movements of the thumb SEMs were 5.8 and 5.5 N, and SDDs 16 N and 15.3 N, respectively.

In patients with nerve injuries the muscle strength is usually assessed with manual muscle strength testing (MMST) and grip and pinch strength dynamometers. Preferably the intrinsic muscle strength should be measured in isolation and quantitatively. The RIHM is a new dynamometer, which allows for measurements of the intrinsic muscle strength in isolation, with reliability comparable to grip and pinch measurements.

Introduction

Ulnar and/or median nerve pathology, e.g. injury, compression or infection (leprosy) causes a strength deficit of the intrinsic muscles which may result in severe loss of hand function. In addition, several neuromuscular diseases (e.g. Charcot-Mary-Tooth, Guillain-Barré) can cause loss of intrinsic hand muscle function.

Muscle strength measurements are frequently made in patients with hand injuries and other hand problems, being an integral part of the physical examination and providing information for diagnosis and for the outcome of surgery and therapy.[1-4] The most commonly used classification scale for manual muscle strength testing (MMST) is the Medical Research Council scale (MRC scale).[5] The MRC uses a 6-point numeric scale (grades 0-5) and suggests a constant distance between points. However, because it is in fact an ordinal scale with disproportional distances between grades, it might have been more appropriate to use terms such as normal, good, fair, trace and paralysed.

With the use of this 6 point ordinal scale for MMST it would be too difficult to identify those factors that may have small but additive beneficial effects and those that may have negative effects on nerve regeneration.[6] In contrast with the MMST, measurements with a dynamometer are more sensitive to change and render outcome on a continuous scale, e.g. kilogram force or Newton. An additional advantage of such measurement methods is that the strength of the uninjured hand can serve as the reference value for "normal" for that person.[7]

In the evaluation of peripheral nerve function, grip and pinch strength measurements with dynamometers have often been recommended as a measure of outcome.[8-10] An important comment of caution in the usage of these dynamometers was made by Strickland et al. who argued that grip and pinch strength data may only be used as an indirect measurement of nerve recovery.[9] It is commonly overlooked that grip strength measurements provide information on the combined function of all the intrinsic and extrinsic muscles of the hand.

We have frequently observed that patients with weak intrinsic muscles of the hand after ulnar and/or median nerve lesion do have a considerable strong grip. The strength of the intrinsic muscles of the hand affect the grip strength only to a certain level. Improvement in grip strength can merely be a reflection of compensatory strengthening of the, non-involved, extrinsic musculature. Therefore, grip strength measurements do not provide decisive information about the motor function of the ulnar and median nerve in the lower arm. However, the hand-surgery literature is replete with grip strength data used to measure the outcome after nerve repair.

If we want to accurately evaluate the outcome of motor function after nerve repair we need to distinguish between extrinsic and intrinsic muscle strength. Clinically this can only be done with a precision instrument measuring the strength of the intrinsic muscles in isolation. Several methods to measure the muscle strength of the hand have been developed.[6 11-15] A number of these instruments can measure the strength of the ulnar-innervated muscles that produce abduction of the index and little finger. Some instruments can measure the strength of the abduction of the thumb. However, in measuring the abduction strength of the thumb the wrist position needs to be controlled to minimise the action of the radial innervated abductor pollicis longus muscle.[3]

A new hand-held dynamometer, the Rotterdam Intrinsic Hand Myometer (RIHM), that meets the specific needs of measuring the intrinsic muscle strength of the hand in isolation has been designed and produced by Experimental Medical Instrumentation (EMI, P.O. Box 1738, 3000 DR Rotterdam, The Netherlands). The RIHM allows measuring the abduction of the little finger and index finger. In addition the opposition and palmar abduction of the thumb can be measured, making two measurements available for both median and ulnar nerve innervated intrinsic muscles.

The aim of the present study is to assess the reliability of measurements with the RIHM in patients with ulnar and/or median nerve injury. Several indexes of measurement error were assessed for intraexaminer applications of strength measurements with this new device and compared with those of reliability studies on grip and pinch strength measurements.

Material and Methods

Subjects

All patients had a laceration of the ulnar and/or median nerve in the forearm, between the elbow and wrist. They were operated by surgeons of the Plastic and Reconstructive Surgery Department and received their hand therapy at the Rehabilitation Department of the same hospital. The therapy protocol consisted of 3-4 weeks of protection for the sutured nerve with a thermo-plastic splint, which in case of combined flexor tendon injuries of the fingers, was a splint with the wrist in 30° flexion and the meta-carpal phalangeal (MP) joints in 60° flexion.

All patients followed a rehabilitation program consisting of exercises to maintain the ROM, strengthening exercises and instruction on how to prevent injuries due to loss of protective sensation. At regular time intervals assessments of muscle strength were done.

The patients included in this study were in different phases of their rehabilitation process. A total of 27 patients (22 male/5 female; mean age 35.4 years, range 16-70 years) with peripheral nerve lesions that were able to exert maximum strength against resistance were included in this study. There were 11 ulnar nerve injuries, 9 median nerve injuries and 7 patients had a combined ulnar and median nerve injury. Two patients had an isolated nerve injury; all others had a combined nerve-tendon injury. The average time period after injury was 4.4 years (range 99 days - 11 years). The majority of injuries were due to sharp objects (e.g. glass, knife) causing injury to the forearm between the elbow and wrist.

The measurement protocol was explained to the patients and all gave written informed consent. The ethical board of the Erasmus MC – University Medical Center Rotterdam approved this study.

Instrument

Measurements were performed by means of the Rotterdam Intrinsic Hand Myometer (RIHM). Compared to a generic industrial dynamometer, the RIHM is a dynamometer with the advantage of an easy-to-hold, ergonomic handgrip and a different method of giving resistance i.e. by means of pulling, in which the angle of the applied strength is easy to control. Another advantage of the RIHM is that opposition of the thumb can be tested. This provides us with two tests for both the ulnar and median nerve innervated muscles, which is valuable when comparing the muscle strength recovery of both nerves.

The RIHM was developed because in a previous study we found that with a generic industrial dynamometer, only relatively large changes in muscle strength measurement of the thumb, index and little finger could be adequately detected.[16]

Testing protocol

The measurements were done in the clinical setting of a Rehabilitation department. The examiner and patient were seated at opposite sides of a table. The patient was shown how to hold the finger or thumb and instructed that he/she should try to keep the finger or thumb in that position with maximum strength. The strength on the finger or thumb was slowly increased while the examiner verbally encouraged the patient to hold the finger or thumb in place, which is known as a break test.[17] The places at which the strength was applied were similar to the anatomical reference points of the manual muscle testing as described by Brandsma et al.[3 18]

For the ulnar nerve innervated muscles, two measurements were done:

- Ulnar abduction of the little finger. The patient’s hand was in supination while the second, third and fourth fingers were held by the examiner’s hand. The patient’s little finger was placed in maximum abducted position with the MP joint in slight flexion. The patient was told to keep the finger in that position while the sling of the dynamometer was applied at the PIP joint of the little finger. The pull was always perpendicular to the little finger in a straight line with the palm of the hand.

- Radial abduction of the index finger (mainly the first dorsal interosseous muscle). The patient's hand was in pronation and the third, fourth and fifth fingers were held by the examiner. The point at which the sling was applied was at the radial side of the PIP joint of the index finger. The pull was always perpendicular to the finger; parallel to the palm of the hand

For the median nerve innervated muscles, two measurements were done:

- Palmar abduction of the thumb. (or anteposition[19]) The lower arm was in supination with the elbow resting on the table with the wrist manually supported by the examiner in dorsiflexion. The sling was applied at the MP joint level of the thumb. The patient was asked to move the thumb away from the palm of the hand. The strength was in one line with the flexion-extension axis of the MP joint of the thumb.

- Opposition of the thumb. The lower arm was supinated and all fingers of the hand were fixed flat on the table by the examiner. The pull was at the MP joint in a horizontal plane in line with the palm of the hand. The patient was instructed not to flex the interphalangeal joint of the thumb.

All movements were tested three times within one session; after a short break in which the patient left the testing position, the same examiner performed a second session. All measurements were completed within 30 minutes.

Statistics

The reliability indexes intraclass correlation coefficient (ICC) and the standard error of measurement (SEM) were calculated. Although both of these measures are related they define different properties. The magnitude of the ICC defines a measure's ability to discriminate among subjects, and the SEM quantifies measurement error in the same unit as the original measurement (Newton).[20-26]

An analysis of variance (ANOVA) was performed with a SPSS/PC+ 10.1 version program to determine the multiple sources of measurement error. We calculated the variances attributed to differences between patients differences, between sessions, and the interaction between these factors, also including some residual error from non-specified error sources. The total variance minus the variance between patients constitute the error variance, from which the SEM is computed as its square root.

The magnitude of change between tests which is required to detect a real change in a subject's performance is indicated as the smallest detectable difference (SDD). This SDD represents the magnitude of the measured difference, of which the examiner can be (95%) confident that a genuine change of strength has taken place rather than a change due to measurement error. The SDD can be calculated by multiplying the SEM with $1.96 * \sqrt{2}$. The smaller the measurement error, the better the measure.[23]

Since no clear criteria to judge the SDD are available for such measurements we compared our findings with a previous study investigating grip and pinch strength measurements in a group of patients with hand injuries. For this comparison we expressed the

SDD in relation to the SD of the measurements, which was labelled as the SDD/SD ratio.[27]

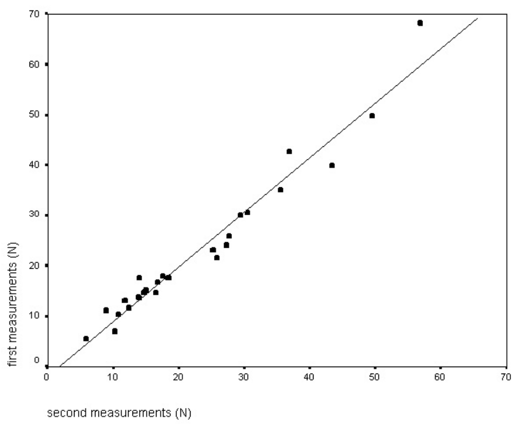
Results

Table 1 gives the mean value and standard deviation (SD) of all measurements (two ulnar and two median nerve measurements). The strength of the thumb measurements was considerably larger than that of the little finger and index finger. Results of the two measurement sessions of the index finger, little finger and thumb abduction and opposition of the thumb are shown in four scatter plot diagrams (Figures 1, 2, 3 and 4). These figures show a high level of correspondence between the two sessions.

Table 1. Two sessions of muscle strength measurements of four movements of the hand with a hand-held dynamometer in patients (n=27) with an ulnar and median nerve injury. (Newton)

	Session 1			***Session 2***		
	Mean(N)	***SD***	***range***	***Mean(N)***	***SD***	***range***
Abduction little finger	22.8	14.5	5.6 - 68.2	22.6	13.1	5.9 - 56.8
Abduction index finger	27.3	18	4.7 - 60.6	28.5	17.9	7.1 - 61.7
Abduction thumb	55	24.2	13.5 - 101	55.3	23	13.9 - 101.7
Opposition thumb	86.9	25.6	50.8 - 144.2	85.9	24.8	41.7 - 142.5

Figure 1. and 2 Scatter plot of two sessions of measurements of the force of the abduction of the little and index finger.



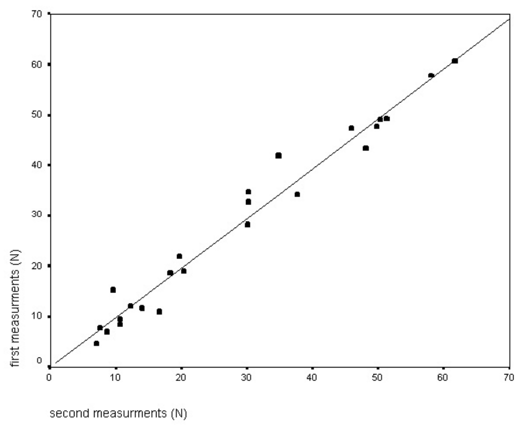
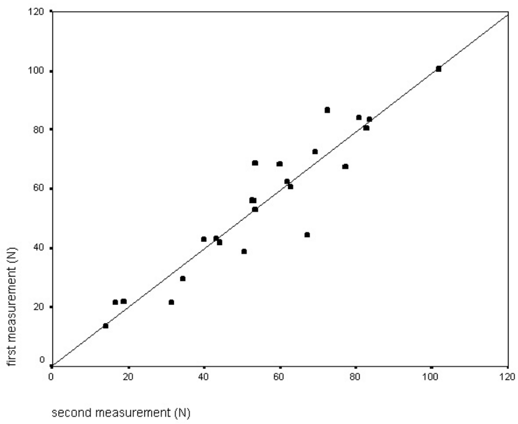


Figure 3 and 4 Scatter plot of two sessions of measurements of the force of the abduction and opposition of the thumb.



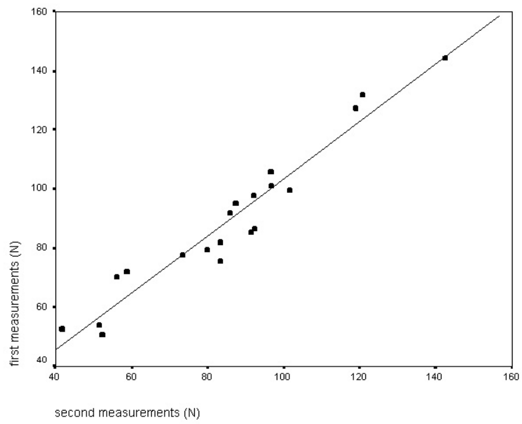


Table 2 gives data on ICC, SEMs and SDDs for the intraexaminer measurements of all four tests. The ICCs of all measurements were greater than or equal to 0.94. For the ulnar innervated muscles the SEM for abduction of the little finger and index finger were 2.2 and 2.3 N, while the SDDs were 6.1 and 6.3 N respectively. The SEM for the median nerve innervated muscles of abduction and opposition of the thumb were 5.8 and 5.5 N, respectively, while the SDDs were 16 N and 15.3 N.

Table 2. Reliability indexes (ICC, SEM, and SDD) for measurements with a hand-held dynamometer in 27 patients with ulnar and median nerve paralyses.

Nerve	***Movement tested***	***ICC***	***SEM (N)***	***SDD (N)***	***SDD/SD ratio****
Ulnar	Abduction little finger	0.97	2.2	6.1	0.4
	Abduction index finger	0.98	2.3	6.3	0.4
Median	Abduction thumb	0.94	5.8	16	0.7
	Opposition thumb	0.95	5.5	15.3	0.6

* SDD/SD ratio is presented for comparison of SDD with grip and pinch strength measurements

To summarise, only differences between two measurements greater than 6.3 N can be interpreted as a real change in assessing the strength of the abduction of the little and index finger and for the median innervated muscles of the thumb this value is 16 N.

To allow comparison with the results of the present study, Table 3 gives data on grip and pinch strength measurements from a study on 33 patients with hand injuries.[27] It can be seen that the RIHM has similar reliability with regards to ICC and error measurement compared with the grip and pinch strength measurements. The ICCs for the RIHM measurements were between 0.94-0.98 compared to 0.93 – 0.97 for the grip- and pinch strength measurements, which according to the scale suggested by Shrout et al.[28] should be classified as excellent. The SDD/SD ratios for the RIHM were between 0.4 and 0.7, for the grip and pinch, measurements they were comparable; between 0.5 and 0.7, respectively.

Table 3. Reliability study of 33 patients with hand injuries. (intra-examiner, experienced examiner)

	mean (N)	***SD(N)***	***ICC***	***SEM (N)***	***SDD (N)***	***SDD/SD ratio***
Grip strength (2nd handle position)	250	123	0.97	22	61	0.5
Grip strength (4th handle position)	231	110	0.95	25	70	0.6
Tip pinch strength	39	17	0.93	4	12	0.7
Key pinch strength	64	22	0.97	4	11	0.5

Discussion

The intrinsic muscles of the hand have their origin and insertion within the hand. There are four dorsal interosseous muscles, three palmar interosseous, two ulnar lumbricals and the adductor pollicis muscle innervated by the ulnar nerve. The intrinsic muscles innervated by the median nerve are the abductor pollicis brevis muscle, opponens pollicis muscle and two radial lumbricals. Both ulnar and median nerves usually innervate the flexor pollicis brevis muscle. Many valuable studies on the function of the intrinsic muscles of the hand have been performed.[17 29-34]

The widely used manual muscle strength testing, grip strength measurements and pinch strength dynamometers provide important information on the recovery of muscle strength after peripheral nerve injury, but also have considerable limitations. Grip strength is a vital function of the hand in general since it is essential in activities of daily living. However, in our opinion it is a less adequate parameter to evaluate the muscle strength of the intrinsic muscles of the hand. Grip strength is not only a reflection of both the long and short flexor musculature of forearm and hand[35] but is also dependent on the strength of the extensor muscles.[36] When measuring grip and pinch strength, the question will remain what the contribution of the intrinsic muscles to grip and pinch strength is. Consequently, an instrument that is capable of measuring the intrinsic muscle strength in isolation is preferable in evaluating the recovery of muscle strength in the ulnar and median nerve injuries.[16]

In this study we tested the reliability of measurements with the RIHM for the intrinsic muscle strength measurements in 27 patients with ulnar and/or median nerve injury. The results show that the reliability of the RIHM, as determined by the ICC, was excellent. We have only examined the intra examiner reliability, since this is the most occurring situation with these measurements in clinical practice.

The SDD for the ulnar and median nerve innervated muscles were 6.3 N and 16 N respectively. The amount of measurement error considered to be acceptable is a matter of clinical judgement. One useful approach is to judge the SDD in relation to the SD of the measurements. We have applied the same method and compared these with data from our reliability study of grip and pinch strength measurements (Table 3).

To determine the clinical value of a particular measurement in a specific population it is essential to know in which range the changes of muscle strength take place. For example, in patients with hand injury, the grip strength will have weakened shortly after the trauma. In later rehabilitation phases the increase of muscle strength will generally reach a plateau after many months. If the difference in the grip strength between the start and end of the rehabilitation is for example 100 N, an SDD of e.g. 80 N will reveal the measurements to be inadequate to detect changes. If the range in which the strengths change is as wide as 300 N, an SDD of 30 N is certainly sufficient to detect changes during the rehabilitation process. In this latter example a virtual scale of 10 steps is achieved.

It can be seen that both ICC values and SDD/SD ratios are very similar for intrinsic muscle strength measurements and grip and pinch strength measurements.

Until now, manual muscle strength testing and pinch and grip strength measurements with dynamometers are the most widely-used tools to assess the muscle strength of the hand after nerve injuries though both have important limitations in determining the strength of the intrinsic muscles. The RIHM is a new dynamometer, which allows for measurements of the intrinsic muscle strength in isolation. The reliability of measurements with the RIHM is comparable to grip and pinch strength measurements and is acceptable to study the recovery and function of the intrinsic muscles of the hand in isolation. The measurements with the RIHM are a valuable addition to the existing instruments in the evaluation of nerve function of the hand.

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CHAPTER 9

Long term outcome of muscle strength in patients with ulnar and median nerve injury: *Comparing manual muscle strength testing, grip and pinch strength dynamometers and a new intrinsic muscle strength dynamometer*

Normally, the movements of the interphalangeal joints are beautifully coordinated and the metacarpophalangeal joint can be stabilized or maintained in an infinite number of mutually varying positions.

J.M.F. Landsmeer (1919-1999)
The coordination of finger-joint motions
J Bone Joint Surg (Am) 1963; 45 A(8)

Accepted *Journal of Rehabiliation Medicine*

Ton A.R. Schreuders, Marij E. Roebroeck, Jean-Bart Jaquet, Steven E.R. Hovius and Henk J. Stam. Long term outcome of muscle strength in patients with ulnar and median nerve injury: Comparing manual muscle strength testing, grip and pinch strength dynamometers and a new intrinsic muscle strength dynamometer. *J Rehabil Med* 2004; 36 (reprinted with permission)

Abstract

Objective: To compare the outcome of the muscle strength with manual muscle strength testing grip and pinch strength measurements and a dynamometer which allows for measurements of the intrinsic muscles of the hand in isolation (the Rotterdam Intrinsic Hand Myometer, RIHM).

Method: Thirty-four patients more than 2 years after ulnar and/or median nerve injury. Muscle strength was evaluated using manual muscle strength testing (MMST), grip, pinch and intrinsic muscle strength measurements.

Results: Manual muscle strength testing showed that most muscles recover to grade 3 or 4. Average grip strength recovery, as percentage of the uninjured hand, was 83%. Pinch strength recovery was 75%, 58% and 39% in patients with ulnar, median and combined nerves injuries, respectively. The RIHM measurements revealed a poor recovery of especially the ulnar nerve innervated muscles (26-37%). No significant correlation (Pearson) was found between the measurements of the RIHM and grip strength. Pinch strength was significantly correlated with strength of the abduction of thumb and opposition of the thumb strength (r 0.55 and 0.72, p = .026, .002) as measured with the RIHM.

Conclusions: While manual muscle strength testing and grip strength measurements show a reasonable to good recovery, measurements of the intrinsic muscles by means of the RIHM showed poor recovery of the intrinsic muscle strength after peripheral nerve injury. No correlation was found between the recovery of the intrinsic muscle strength and the grip strength measurements.

Introduction

Peripheral nerve lesions constitute a major reason for severe and longstanding impairment in hand function[1]. Outcome is often unpredictable and disappointing with poor recovery of sensibility, loss of motor function, cold intolerance and pain, leading to loss of function, limitations in activities and social participation[2] and can cause considerable psychological stress.[3] The most frequently used method to evaluate the outcome of motor function is the manual muscle strength testing (MMST) introduced by the British Medical Research Council (MRC) 0-5 scale.[4] In addition to MMST, grip and pinch strength measurements with dynamometers are increasingly becoming a standard for evaluation of the outcome of peripheral nerve function [5-11]. There are, however, reasons to question the appropriateness of the present methods in evaluating the recovery of muscle strength after peripheral nerve injuries. Firstly, measuring the recovery with the MMST using the ordinal MRC scale provides too little differentiation in the 4-5 segment of the scale.[12] Secondly, grip and pinch strength measurements provide information on the strength of the combined action of all the muscles of the forearm and hand, and not exclusively of the median or ulnar nerve innervated intrinsic muscles. Thirdly, traumas of the forearm usually involve injuries of associated tissues, e.g. flexor tendons, which will have a negative effect on the grip strength.[13-15]

To avoid the aforementioned difficulties, quantitative measurements which can specifically measure the intrinsic muscle strength are required. Such instruments have been developed, e.g. to measure the abduction strength of the thumb[16-19] or the Mannerfelt intrins-o-meter to measure the abduction strength of the little and the index finger.[20] The Rotterdam Intrinsic Hand Myometer (RIHM) is a new dynamometer which enables to measure two intrinsic muscle movements for the ulnar nerve innervated movements; i.e. abduction of index and little finger, and two for the median nerve innervated intrinsic muscles of the thumb; i.e. palmar abduction and opposition of the thumb. Reliability and measurement error in patients with peripheral nerve injuries are reported to be acceptable.[21]

The aim of this study was to compare the long term outcome of muscle strength in patients with ulnar and median nerve injuries assessed by means of MMST, grip and pinch strength measurements and by means of dynamometric measurements of the intrinsic muscles with the the newly developed RIHM.

Material and method

We requested patients who had suffered a unilateral traumatic median, ulnar, or combined median ulnar nerve injury, which were primarily repaired by surgeons specialised in hand surgery, to participate in this study. Thirty-four patients (28 men/6 women) with a mean age of 36 (range 16-70, SD 12.7) years, who had suffered an injury more than two years previously, were included. The average time between the assessment and the injury was 7.3 (range 2.1 – 32.2 years; SD 6.4) years. Of the 34 patients 27 patients (79%) sustained an injury to one or more tendons and major blood vessels, 6 patients (18%) to one or more muscle bellies and two patients had a fracture. Only 4 out of the 34 patients had an isolated nerve injury. In 42% the left hand, and in 58% the right hand was injured, respectively. In 65% the dominant hand was injured including the two left hand dominant patients.

Patients were divided into three groups; ulnar nerve injury (14 patients), median nerve (12 patients) and combined ulnar and median nerve injury (8 patients). All injuries were in the forearm located between the elbow and the wrist.

Patients had attended the rehabilitation department and were treated according to a standard hand therapy protocol.[22] The sutured nerve was protected for 3-4 weeks with a splint to prevent tension on the nerve. The 4-6 weeks following this first phase patients visited the rehabilitation department 1-2 times a week for exercises to regain full mobility. Patients were taught exercises to prevent contractures and wounds to the insensate parts of their hand. Following this period patients were usually attending the

Rehabilitation department once a month when routine nerve assessments were done.

Four methods of measuring the muscle strength of the hand were studied. Firstly, intrinsic muscle strength was assessed by use of MMST according to Brandsma et al.[23] Four movements were measured; the abduction of little and index finger for the ulnar nerve, and abduction and opposition of the thumb for the median nerve. In addition, we examined whether patients were able to adduct the little finger and move the middle finger sideways. An inability to adduct the little finger is called the Wartenberg sign[24] and the inability to ab- and adduct the middle finger is the Egawa sign[25], both signs of ulnar nerve muscle weakness.

Secondly, grip and pinch strength measurements were performed with the Lode “hand grip” and “pinch grip” dynamometers, (produced and distributed by Lode Medical Technology, Zernikepark 16, 9747 AN Groningen, The Netherlands) which are similar to the Jamar and Preston dynamometers. For the grip strength measurements the second handle position was used (distance between the handles of 4.6 cm) and for the pinch strength measurements the “tip-to-tip” pinch was done between the tip of the index finger and thumb, with the other fingers flexed. According to the recommendations of the American Society of Hand Therapists (ASHT)[26] participants were comfortably seated at a table on which the dynamometers were positioned. The subjects were told to keep their shoulders adducted and their elbow flexed without resting their arm or the grip handle of the dynamometer on the table. After an explanation of the tasks, the examiner told each subject, “Squeeze the dynamometer as hard as you can”, and “Go”. No feedback regarding the performance was given during the measurement. Measurements were obtained of the left and right hands alternately, and for each measurement, the mean of 3 repetitions was recorded.

Finally, the RIHM was used to measure the strength of the intrinsic muscles of the hand. As with MMST, the same four movements were tested and were performed with a comparable procedure concerning e.g. the hand position, position of applying pressure, and instructions:

The patient was seated with their elbow resting on the table. The examiner showed how to hold the finger or thumb and instructed the patient to keep it in that position with maximum strength. A breaktest was performed in which the examiner slowly increased the force on the patient’s finger or thumb, while encouraging the patient to hold the finger or thumb in place. All the measurements were performed within half an hour on the same day by one person, who was an experienced examiner (TARS).

For the ulnar nerve innervated muscles, two measurements were done:

- Ulnar abduction of the little finger. The patient’s hand was in supination while the second, third and fourth fingers were held by the examiner’s hand. The patient’s little finger was placed in maximum abducted position with the metacarpal phalangeal (MP) joint in slight flexion. The patient was told to keep the finger in that position while the sling of the dynamometer was applied at the proximal interphalangeal (PIP) joint of the little finger. The pull was always perpendicular to the little finger in a straight line with the palm of the hand.

- Radial abduction of the index finger (mainly the first dorsal interosseus muscle). The patient's hand was in pronation and the third, fourth and fifth fingers were held by the examiner. The point at which the sling was applied was at the radial side of the PIP joint of the index finger. The pull was always perpendicular to the finger; parallel to the palm of the hand.

For the median nerve innervated muscles, two measurements were done:

- Palmar abduction of the thumb. The lower arm was in supination with the elbow resting on the table with the wrist manually supported by the examiner in dorsiflexion. The sling was applied at the MP joint level of the thumb. The patient was asked to move the thumb away from the palm of the hand. The strength was in one line with the flexion-extension axis of the MP joint of the thumb.

- Opposition of the thumb. The lower arm was supinated and all fingers of the hand were fixed flat on the table by the examiner. The pull was at the MP joint in a horizontal plane in line with the palm of the hand. The patient was instructed not to flex the interphalangeal joint of the thumb.

Measurement results were expressed as the “percentage recovery” of the uninjured hands. Evaluating motor function recovery as a quantitative percentage of the uninjured side provides a useful method of normalising the results to compensate for the variability of patient strength.[18] Of the measurements with the dynamometers the mean and SD were calculated. In 10 measurements of 6 patients muscle strength was less than grade 3 (Table 1). In these cases RIHM dynamometry was not possible because no resistance could be given in these cases a “0” score was recorded.

For abduction of the little and index finger, the relation between the four different methods of muscle strength testing was assessed in patients with a single ulnar nerve injury and in those with combined ulnar and median nerve injuries (n=22). In the same way, for both thumb movements, one group was formed of patients with median nerve and combined injuries (n=20).

The relation between the MMST and RIHM dynamometry muscle strength testing was assessed by calculating the Spearman correlation coefficient. The Pearson correlation coefficient was calculated between the percentage recovery as measured with the three dynamometers for grip strength, pinch strength and intrinsic muscle strength (RIHM).

Results

The outcome of muscle strength as measured with the MMST according to the MRC 0-5 scale is reported in Table I. Most of the movements tested, i.e. 50 of 52 measurements (96%) in the ulnar and median nerve injury group, recovered to grade 3 or better. For the group of 8 patients with both ulnar and median nerve injured, 24 of 32 measurements (75%) were grade 3 or better. The Wartenberg sign was present in 18 of the 22 ulnar nerve injured hands (82%). The Egawa sign was present in all patients with an ulnar nerve injury.

Table I: Outcome of muscle strength in 34 patients with ulnar and/or median nerve injuries as assessed with the manual muscle strength testing method (MMST) according to the Medical Research Council (MRC) (grades 0-5).

	Ulnar nerve lesion (n=14)		**Median nerve lesion (n=12)**	
MRC Grade	**Abduction little finger**	**Abduction index finger**	**Abduction thumb**	**Opposition thumb**
0	-	-	-	-
1	-	-	-	-
2	1	-	1	-
3	10	13	1	2
4	3	1	7	5
5	-	-	3	5
	Combined ulnar and median nerve lesions (n=8)			
0	1	2	-	-
1	-	-	-	1
2	-	1	2	1
3	4	4	3	4
4	3	1	2	2
5	-	-	1	-

Figures 1 and 2 present the relation between the muscle strength grading of MRC grades 3, 4 and 5 as compared to the RIHM measurements in Newton (N). The grade 5 measurements refer to the uninvolved hands of the 34 patients. Of the median nerve injured hands the four measurements with MRC grade 5 were included.

Figure 1: Strength of the abduction of the little finger: assessed by means of MRC grade 3, 4 and 5 and measured with the RIHM dynamometer (N). The box represents the interquartile range, which contains the 50% of values. The whiskers are lines that extend from the box to the highest and lowest values. The line across the box indicates the median. The MRC values grade 5 are of the uninvolved hand.

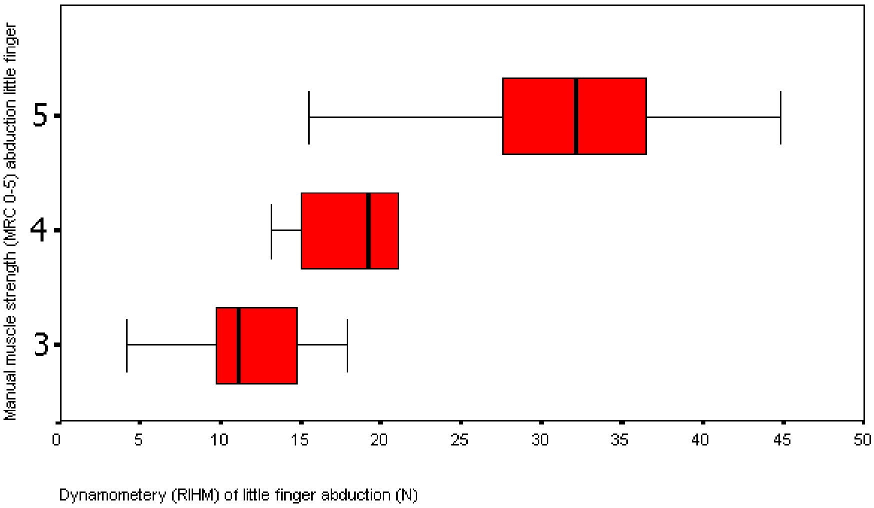
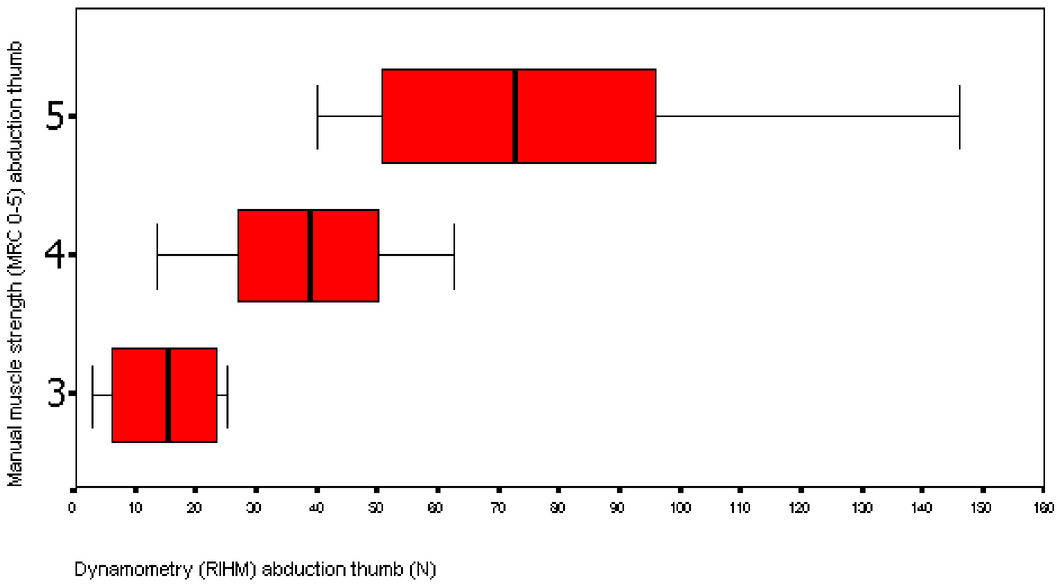


Figure 2: Strength of the abduction of the thumb: assessed by means MRC grade 3, 4 and 5 and measured with the RIHM dynamometer (N). The box represents the



interquartile range, which contains the 50% of values. The whiskers are lines that extend from the box to the highest and lowest values. The line across the box indicates the median. The MRC grade 5 values are of the uninvolved hand with the 4 grade 5 grades of the uninvolved hands.

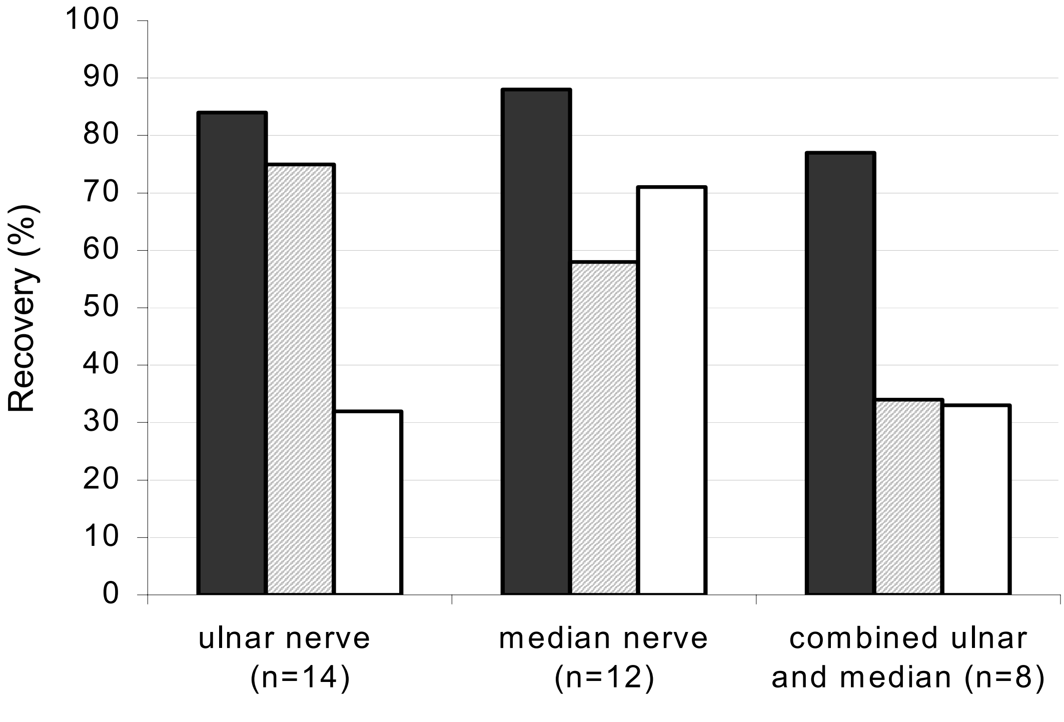
Table 2 presents the outcome of the muscle strength, expressed as "percentage recovery" of the uninjured hand, of grip and pinch strength measurements and the RIHM measurements of the four movements. The average outcome of grip strength in the three groups of patients was comparable; i.e. 77 to 88%. Loss of pinch strength is greatest in patients with the combined nerve injuries, and is greater in patients with a median nerve injury than in patients with an ulnar nerve injury. The abduction of the index finger strength as measured with the RIHM in 14 ulnar nerve injured hands is remarkably low; only 26% of the uninjured side. The abduction of the thumb strength in patients with single median nerve and combined nerve injuries was 59% and 27% of the uninjured hand, respectively.

Table 2: Outcome of muscle strength as percentage (mean and SD) of the uninjured hands measured with grip, pinch and intrinsic muscle strength (RIHM) dynamometers.

			RIHM			
	Grip	**Pinch**	Abduction little finger	Abduction index finger	Abduction thumb	Opposition thumb
Ulnar nerve (n=14)	84 (15)	75 (14)	37 (22)	26(13)		
Median nerve (n=12)	88 (21)	58 (22)			59 (31)	82 (21)
Combined ulnar and median nerve (n=8)	77 (18)	34 (30)	45 (35)	25 (22)	27 (25)	36 (28)

RIHM = Rotterdam Intrinsic Hand Myometer

Figure 3: Average percentage recovery of grip ■, pinch ░ and intrinsic □ muscle strength of three groups of patients; ulnar nerve, median nerve and



combined nerve injury.

Figure 3 presents the average percentage recovery of the intrinsic muscles compared to grip and pinch strength measurements for the three groups of patients.

There was a significant relation found between MMST and the RIHM dynamometry measurements of all four movements (Table 3); Spearman correlation coefficients were 0.65, 0.63, 0.85 and 0.56 for little finger, index and thumb abduction and opposition of thumb, respectively (p-values from 0.001 to 0.014). No significant correlation was found between the four measurements of the RIHM and the grip strength measurements. Pinch strength was significantly correlated only with strength of the abduction of thumb and opposition of the thumb strength (Pearson r; 0.55 and 0.72, p = 0.026, 0.002) as measured with the RIHM. Pinch strength was not correlated with grip strength measurements.

Table 3; Correlation between different muscle strength testing methods.

	RIHM measurements			
	Abduction little finger (n=21)	Abduction index finger (n=21)	Abduction thumb (n=20)	Opposition thumb (n=20)
Manual muscle strength	0.65*	0.63*	0.85*	0.56*
Grip strength [b]	ns	ns	ns	ns
Pinch strength [b]	ns	ns	0.55*	0.72*

RIHM = Rotterdam Intrinsic Hand Myometer. [a] = Spearman correlation coefficient, [b] = Pearson correlation coefficient, * (p<0.05), ns = not significant

Discussion

The evaluation of muscle strength is, in combination with the assessment of sensibility, an important clinical method to determine ulnar and median nerve function. This information is valuable in decision-making concerning surgery (e.g. tendon transfers), therapy (e.g. splints), advice in work-related issues (e.g. safety to work with machines) and research issues (e.g. nerve repair technique). Concerning this latter topic, Trumble et al.[18] noted that without extremely sensitive methods for monitoring the functional outcome of nerve regeneration, it will be difficult to identify those factors that may have small but additive beneficial effects and those that may have negative effects on nerve regeneration.

MMST according to the MRC method (grades 0-5) is the most widely used clinical method to measure muscle strength. MMST is the only instrument which is useful in the MRC 0 - 2 grades i.e.in the early phases of nerve recovery. Grade 3 is an important cut-off point; the muscles are just strong enough to provide a full range of motion on all the joints that the muscle crosses. When the muscles have reached this level of recovery usually there is no risk of joint contractures. Grade 3 can be easily determined, in contrast to grade 4 which is defined as "complete range of motion with some resistance", while grade 5 is defined as the ability to hold against "maximum pressure". Objective assessment of "some resistance" and "maximum pressure" will depend on the experience and subjective judgement of the examiner.

Besides the problem with the grading, there is disagreement as to what constitutes a functional level of muscle strength recovery after peripheral nerve injury using grades 0-5. In literature, useful or functional motor recovery has been defined anywhere from 2+ level of recovery to a 4-5 level.[24] Seddon[27] defined a "good" motor outcome as grade 3 or better and reported that 47.6% of his patients with nerve injuries obtained this level. Frykman [28] reached a higher percentage of grade 3 or better; 81% and 64% after median and ulnar nerve injuries, respectively. Strickland et al.[24] selected grade 4 for determining a good result, which was obtained in 9 of 17 patients with ulnar nerve injuries. In the patients in the present study, very few measurements of the intrinsic muscles (9/84) reached grade 5. Of all the 84 MMST measurements 75% were grade 3 and 4.

Although it is imperative to come to an agreement as to what should be considered as a good motor outcome on the MRC scale, the more important question is whether this method is sensitive enough to sufficiently differentiate above the grade 3 level. We consider MMST to be an important and useful method in the 0-3 grades of the MRC scale, but for strength measurements above grade 3 a more accurate evaluation method is required. Grip and pinch strength dynamometry is a more sensitive method to determine muscle strength and to render outcome on a continuous scale, e.g. kilogram force or Newton. These quantitative outcomes, which will also facilitate statistical analyses, have been proposed as a standardised method to evaluate motor recovery in patients with peripheral nerve injuries.[5 7 8] Reliable application of these measurements requires little training and is not influenced by the experience of the examiner.[29] Another benefit is that evaluating motor function recovery as a percentage of the uninjured side is possible using the uninvolved hands as the normal level of strength for that patient. Therefore the data can be normalised and allows to compensate for the large variability in patient strength.

In our study the mean recovery of grip strength, compared with the uninjured hand, was 84% in the 14 patients with an ulnar nerve injury. Rosén [7] and Strickland et al.[24] found comparable grip strength recoveries of 88 and 89.9%, respectively. Commenting on these grip strength results, Strickland et al.[24] made a noteworthy remark that grip and pinch strength may only be used as an indirect measurement of ulnar nerve outcome. Although grip strength measurements do fulfil the requirements for quantitative outcome of the strength of the hand, they cannot differentiate between the intrinsic and extrinsic muscles. Strong grip strength does not necessarily coincide with strong intrinsic muscles. The results of the present study give more specific insight in the recovery of the intrinsic muscle strength.

It remains debatable what the precise contribution of the intrinsic muscles are in grip and pinch strength measurements.[30 31] It has been suggested that the most narrow handle position (position 1) of the

Jamar could be used to test the strength of the intrinsic muscles, whereas the wider handle (position 4 and 5) could be used to test the extrinsic finger flexors.[32] In another study EMG recordings of hand muscles in sustained grasp in the different handle positions seems to confirm this, but again it was concluded that the strength of the intrinsic muscles could not be isolated from that of the extrinsic muscles.[33]

In our study results there was a remarkable discrepancy between the poor outcomes of the intrinsic muscles strengths as measured with the RIHM and the high levels of outcome of grip strength in patients with ulnar nerve injuries. Rosén[7] obtained similar values using the Mannerfelt "intrins-o-meter" and found a recovery percentage for the ulnar nerve innervated muscles of 31 and 36% for abduction of index and little finger, respectively, while the average grip strength recovery was 88%.

In our study no correlation was found between the recovery of the intrinsic muscle strength and the grip strength measurements. This seems to affirm our assumption that recovery of grip strength does not reflect the recovery of the intrinsic muscles of the hand after peripheral nerve injury. Thus, outcome of the intrinsic muscles strength with the RIHM dynamometer is a valuable addition to grip and pinch strength measurements in patients with peripheral nerve injuries. The RIHM measurements might have further use in evaluation of the intrinsic hand muscle strength in e.g. leprosy, neuropathies like hereditary motor and sensory neuropathy and Guillain-Barré syndrome.

Examining the pinch strength outcome, the loss of pinch strength was noticeably greater in the median nerve injury group of patients than in the ulnar nerve injury group. Pinch strength measurements were not significantly correlated with the strength measurements of the abduction of the little and index finger, but were correlated with the intrinsic muscle strength measurements of the thumb. It appears from these results that positioning of the thumb by the abductor pollicis brevis and opponens pollicis muscles is an important requirement for a strong pinch.

Another notable finding in this study was the good recovery of the thumb intrinsic muscle strength in patients with median nerve injury, which is in contrast with the poor recovery of the abduction of little and index finger strength in patients with ulnar nerve injury. An explanation might be that the test for the thumb muscle strength is more affected by synergistic muscle activity e.g. of the ulnar nerve innervated part of the flexor pollicis brevis muscle or due to crossover of ulnar innervation.[34] Frykman et al.[24] estimated that 50% of the evaluated patients would have satisfactory thumb opposition even if no median nerve re-innervation occurred. Brand[35] mentioned another synergistic movement of the thumb palmar abduction while testing the abductor pollicis brevis due to bowstringing of the radial nerve innervated abductor pollicis longus muscle with the wrist in flexion. For this reason examiners should test the abductor pollicis brevis of the thumb with the wrist in extension. This position is not always possible with the dynamometer measurements shown in other studies but can be accomplished with the RIHM dynamometer.

A limitation in our study is that there were only 8 patients in the third group, i.e. those with both ulnar and median nerve injury. Two patients in this group had a remarkably good recovery (i.e. grip strength recovery of 98 and 91%). In one patient, with an ulnar and median nerve injury at the wrist level, the abduction strength of the little finger recovered to 93%. Because the results of this patient had a strong impact on the average strength of the group, we probably overestimated the average abduction strength of the little finger and the grip strength for patients with combined ulnar and median nerve injuries.

Conclusion

In conclusion the measurement methods used to determine the recovery of the motor function of ulnar and median nerve injured hands need further consideration. In patients who sustained an ulnar nerve injury the mean recovery of the abduction force of the index finger was only 26% of the uninjured side. The abduction of the thumb strength in patients with single median nerve and combined nerve injuries was 59% and 27% of the uninjured hand, respectively. We regard these average percentages recovery as poor, especially in contrast with the grip strength percentages of 77 to 88% recovery.

A dynamometer like the RIHM provides a more accurate clinical assessment of the outcome for two reasons. Firstly, with the RIHM intrinsic muscle strength is measured in isolation, in contrast to grip and pinch strength measurements in which many uninvolved muscles are tested besides the intrinsic muscles. Secondly, because of its quantitative results the RIHM measurements provide a more accurate clinical assessment as compared with the MMST especially in MRC grades 4 and 5.

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CHAPTER 10

Discussion

Together with the brain, the hand is the most important organ for accomplishing tasks of adaptation, exploration, prehension, perception and manipulation, unique to humans.

Chao EY, An K-N, Conney WP, Linscheid RL.
Biomechanics of the Hand: A Basic Research Study (1989)

The main purpose of this thesis is to study different methods of measuring muscle strength of the hand and to develop a reliable instrument to quantitatively measure the strength of the intrinsic muscles of the hand. Such an instrument would allow the function of the intrinsic muscles to be studied in clinical practice. This can be valuable in monitoring the recovery or deterioration of the intrinsic muscle strength of the hand in patients who have suffered from nerve injuries in their arm. Intrinsic muscle strength could also be examined in other neuromuscular diseases which affect the intrinsic muscles, such as Charcot-Marie-Tooth disease, Amyotrophic Lateral Sclerosis and Guillan Barr˘ syndrome. A reliable instrument which can accurately measure the intrinsic muscle strength may assist in developing more effective therapies.

This final chapter addresses some issues related to measurements of the muscle strength of the hand in a larger perspective and discusses some limitations of this study.

1. How to clinically evaluate nerve function?

Nerve function can be determined by several methods. All of the clinical methods evaluate nerve function indirectly by testing e.g. muscle strength, sensation or sweating. According to Bunnell *the two major functions of the hand are motion and sensation, and these are of equal importance* .[1 p.319] The motor and sensation function is usually reported separately, but some, e.g. Dellon[2] and Rosen et al.[3], present figures on sensation and motor function to provide, conveniently, just one figure as the function or outcome of a particular nerve. In this way the loss of motor function and sensory loss is in accordance with Bunnell s remark, weighed as equally important.

We want to challenge the statement that motion and sensation are of equal importance. It seems to be a reasonable assumption that the consequence of motor and/or sensory loss is dependent on e.g. profession and the patient s ability to adapt to a particular loss of function. One can imagine that a violin player with normal muscle function but loss of sensation would have major difficulties playing the violin, while a farmer with normal sensation but loss of muscle function would be unable to do his work.

As long as it is not precisely known how strength and sensation relate to particular tasks of the hand, it seems more logical to present these results separately when testing the hand.

2. What is the role of sensation in strength measurements?

Brink and Mackel[4] developed a functional and simple test for evaluation of peripheral nerve function. The authors stated that patients suffering from severe sensory neuropathies can perform a wide range of movements, but are unable to sustain constant levels of muscle contraction or perform fine motor adjustments when visual guidance is prevented. They concluded that their results underline the need for sensation in the successful execution of a sequence of co-ordinated, skilful movements.

Studies investigating the ability of the muscles to control the forces of the fingers in gripping objects have shown that decreased sensation is often associated with increased grip strength levels. Grip strength control requires sensory feedback to signal the effectiveness of the motor commands. Sensory feedback uses object properties and mechanical actions, e.g. at the skin-object interface, to modify motor commands; consequently, intact sensory feedback is essential for controlling the grip strength.[5 6]

Complete loss of sensation causes severe problems in hand function. Paul Brand has shown that the loss of protective sensation causes a destructive increase of grip strength.[7 8] He searched for a method to give leprosy patients an artificial (pain) feedback system to protect their hands against injury caused by gripping their tools too powerfully. Experimenting with a prototype he observed a patient who switched the system off when he required a stronger grip. Brand realised that a protective system, which could be switched off, was ineffective.

Apparently, the influence of sensation and pain needs to be considered when interpreting grip strength measurements for the evaluation of nerve function. The above-mentioned studies support the proposition that sensation does play an important role in the control of the muscle strength; however, to our knowledge no study has determined the role of sensation in maximum strength measurements of the hand in a quantitative way.

3. What do grip strength measurements tell us about the intrinsic muscles?

In the above-mentioned book by Sterling Bunnell[1] (1948) one chapter has been dedicated to the intrinsic muscles of the hand. In the introduction Bunnell wrote (p. 467): *the intrinsic muscles of the hand, though tiny, are important because, with the long extensors and long flexors, they complete the muscle balance in the hand. Normal position, normal motion, and even strength of the grip of the hand are dependent on this nice balance of these three sets of muscles* . He also stated that *regarding the function of the intrinsic muscles controlling the fingers is still in the controversial stage* . It is open to discussion how at the same time the role of the intrinsic muscles can be important and controversial, and to what extent the strength of the grip is dependent on the intrinsic muscles.

The contribution of the intrinsic muscles in grip has been studied by e.g. Kozin et al.[9] Twenty-one healthy subjects were given either an initial median nerve block at the wrist followed by an ulnar nerve block, or an ulnar nerve block followed by a subsequent median nerve block. The anaesthetic solution was chosen because of its effectiveness in producing complete motor and sensory block. The average decrease in grip strength was roughly 38% after ulnar and 32% after median nerve block. The total grip loss after both nerves were injected averaged 49% compared with the pre-injection strength.

These results were commented on by Mahaffey[10] who found it surprising that Kozin did not take into account the effect of sensory loss on the results of the grip strength measurements. Both Kozin and Mahaffey agreed that, ideally, motor recovery is best studied with intact sensory function. However, in clinical practice this is rarely seen and results of strength measurements will therefore be influenced by loss of sensation, (see 9.2) especially in these experiments where there is a sudden and complete loss of sensation.

In relation to Bunnel s quotation that strength of grip is dependent on the intrinsic muscle strength, we have observed several patients with poor intrinsic muscle recovery and strong grip strength. In accordance with this observation, in our long-term outcome study (Chapter 9) we found no significant correlation between the grip strength and the strength of the intrinsic muscles as measured with the Rotterdam Intrinsic Hand Myometer (RIHM).[11]

The intrinsic muscle strength may influence the grip strength, but grip strength measurements will not provide sufficient information to assess the precise strength of the intrinsic muscles. This is because in grip strength measurements all the muscles in the lower arm and hand are active making it practically impossible to determine the precise component of the intrinsic muscles. Secondly, loss of sensation will probably also influence the grip strength, making it even more complicated to determine the contribution of the intrinsic muscles.

In clinical practice there is a third reason why grip strength is difficult to interpret when evaluating the intrinsic muscle strength. Generally the peripheral nerves are injured in combination with one or more injuries of the finger and wrist tendons, and it is known that tendon injuries alone cause a decrease of grip strength.[12 13]

4. Is there a relation between muscle strength loss and activities of daily life (ADL) and participation?

Loss of nerve function has an important effect on e.g. hand function and the patients abilities to perform certain tasks. In a group of 81 ulnar and/or median nerve injured patients the mean time off work was more than 31 weeks. Within one year after combined nerve injuries only 24% versus 80% after isolated median, and 59% after ulnar nerve injuries, returned to their work.[14]

Measuring hand function more specifically using the Sollerman test, Rosen found that patients with peripheral nerve injuries had difficulty in picking up coins, putting nuts on bolts and doing up four buttons.[15] Handling these small objects was especially difficult for patients with median nerve loss possibly because of the loss of sensibility of the index and thumb, or due to impaired muscle strength of the thumb. These three selected tasks provided information about the integrated sensory/motor function of the hand and were included in the sensory domain of Rosen s test battery design after nerve repair.[16]

An Indian study of 62 leprosy patients investigated the relation between grip and pinch strength and (using an Indian designed questionnaire) the basic activities of daily living (BADL).[17] The study showed a significant relationship between grip and pinch strengths (in particular the tripod pinch) and the BADL questionnaire.

In a long-term study of patients with peripheral nerve injuries, the relation between the DASH questionnaire and grip strength and sensibility measurements (Semmes Weinstein filaments) was analysed. A strong association was shown between the outcome as measured with the DASH questionnaire for both the sensory and motor recovery.[18 19] Evidently, both functions of the nerve, i.e. sensation and muscle strength, can have an important influence on ADL.

However, interpreting the outcome of tests which assess the patient s ability to perform a certain task by measuring the time taken (Sollerman test) or by asking if the patient has encountered problems (BADL, DASH questionnaires) has some important drawbacks, e.g. they might only assess the patient s ability to adapt or the patient s creativity in finding coping strategies, e.g. in using the non-injured hand or certain trick movements.

Therefore, we propose to present hand function in the domain of function, skills, activities and participation as was suggested by the 2001 World Health Organization report as the International classification of functioning, disability, and health (ICF).[20]

5. Reliability issues

No measurement is perfect: whether it is used to make a diagnosis or to determine a change in strength, measurements will have some error associated with them. Hence, we have to decide how to live with these errors. The primary step is to decide which method to choose to determine the error of measurements.[21]

Studies concerning measuring instruments and methods generally provide Intraclass Correlation Coefficient (ICC) values which are interpreted as showing either good, moderate or poor reliability of the instrument. However, reliability relates to how the measurement will be used, i.e. is the measurement error so large that it would be unlikely to provide valuable information? Estimates of reliability are arranged along a scale and clinicians need to know at what point along this scale they lie and if the change in e.g. muscle strength as measured with the instrument is a clinically relevant deterioration or improvement, or is due to measurement errors only.

Insight in the sources of measurement error can be obtained by performing an analysis of variance. From the error variance, the standard error of measurement (SEM) can be computed as its square root, which is advantageously expressed in the same value as the measurements performed.[22]

Based on the SEM, the smallest detectable difference (SDD) can be calculated as $1.96 \times \sqrt{2} \times SEM$.[23] This SDD can be applied in such a way that only differences between two consecutive measurements greater than the SDD can be interpreted with 95% certainty as real change in strength. If the change between measurements is less than the SDD, the change is interpreted as a result of variation and not as a real change.

Although the calculation of SEM and SDD is becoming an accepted method in reliability studies[21 24-26] to determine the clinical value of a particular measurement in a specific population, it is essential to know in which range the changes of e.g. muscle strength take place. For example, in patients with hand injury, the grip strength will weaken shortly after the trauma. In later rehabilitation phases the increase of muscle strength will generally reach a plateau after many months. If the difference in the grip strength between the start and end of the rehabilitation is, for example, 100 N, an SDD of e.g. 80 N will reveal the measurements to be inadequate to detect changes during the rehabilitation process. If the range in which the strengths change is as wide as 300 N, an SDD of 30 N is certainly sufficient to detect changes during the rehabilitation process. In this latter example a virtual scale of 10 steps is achieved.[27] Whether the SDD is sufficiently small to be acceptable, is a matter of clinical judgement.[28]

In Chapter 3 we considered the SDD of the AIKOH measurements and other instruments proportional to the mean of the measurements; this approach was also suggested by Geertzen et al.[29] In a later phase of this study we reported that the mean may not be the best criterion for this purpose because the mean gives no insight into the range that will be covered from poor to good results.

In a study investigating the interobserver reproducibility of grip strength in patients with lateral epicondylitis, Smidt et al.[25] initially stated that an interobserver difference of 10% of the total range of measurements would be acceptable. Later they found that the correct SDD values of grip strength measurements were larger than the predefined acceptable difference of 10% of the total range of the scale, while for maximum grip strength the SDD approximately equalled the predefined acceptable difference.[30] They concluded that in their study population these outcome measures were insufficiently reproducible to detect changes in an individual patient. In studies comparing larger groups of patients these outcome measures perform adequately because the influence of measurement error decreases with increasing sample size.

In Chapter 5 we proposed to judge the SDD proportional to the standard deviation (SD) rather than to the mean or the range of the measurements. Arbitrarily, we accepted that an SDD/SD ratio should be larger than 0.5 for the instrument to have acceptable SDDs for application in individual patients.[31] Further research is needed to gain insight into the usefulness of this criterion to judge the amount of measurement error.

This SDD/SD ratio should be further studied in different patient groups. We propose that this ratio should be reported in reliability studies of measurement instruments as it will be especially useful for clinicians.

6. Limitations of this study

6.1. Is measuring maximum strength the most appropriate method to measure muscle strength and hand function?

The function of a muscle can be divided into three aspects: force or strength (N), endurance (sec) and velocity (m/sec). In most muscle testing methods, the first aspect, maximum strength is tested, which is sometimes referred to as the maximum voluntary contraction (MVC). In grip and pinch strength measurements this MVC is generally used by asking the patient to squeeze or push *as hard as you can* and has been shown to provide reliable data. In ADL, however, these maximum muscle contractions are rarely used, except for some specific actions, e.g. when lifting a heavy suitcase or opening a tight jar. Usually, a much lower level of strength is needed to perform most of our ADL, especially in white-collar workers. The second aspect, endurance or muscle fatigue, is probably particularly relevant in patients with impaired muscle function due to e.g. multiple scleroses, amyotrophic lateral sclerosis and hereditary motor and sensory neuropathy (HMNS). Videler et al.[32] studied muscle fatigue of grip in patients with HMSN. Many patients with HMSN indicate that during daily activities they experience most difficulty when an activity has to be maintained for a longer period of time.[33 34] Videler and colleagues studied the reproducibility of a fatigue test with measurements of three sets of 15 grip and pinch contractions with a handgrip dynamometer on two separate occasions with a 1-week interval, but found that reproducibility was poor. With regard to instruments to measure muscle fatigue, the authors concluded that no reproducible method is yet available for patients with neuromuscular disorders.

Although many studies have attempted to identify a single muscle fatigue factor, there seems little doubt that the concept of fatigue refers to a class of acute effects that can impair motor performance. Factors known to influence muscle fatigue include muscle blood flow, neuromuscular properties and motivation (sincerity of effort).[35] However, consensus on the definition of muscle fatigue and a standardised method to measure muscle fatigue of the hand are still lacking.

The third aspect of muscle function, the velocity component of muscle function, was not specifically explored in this study. However, it is known that the ability to rapidly move the hand is an important attribute which determines the co-ordination of the hand. The consequences of diminished co-ordination can be observed in patients with spasticity. The patient might have a very strong grip but has major problems in ADL because releasing the grip on an object is not possible. The velocity or co-ordination as part of the muscle function can be evaluated in certain tests that measure time to perform particular tasks.

In Chapter 4, study of lumbrical muscle strength demonstrates that these muscles only have a small strength effect on the metacarpo-phalangeal joint flexion of the fingers. The interossei muscles are much stronger than the lumbricals. The importance of the lumbrical in fast movements rather than in maximum strength circumstances, as suggested by Leijnse et al.[36], is interesting and warrants further clinical study.

6.2. Measurement of strength over time

In the long-term outcome study presented in Chapter 9 the muscle strength of patients hands was mainly measured at a certain point in time (cross-sectional). We have not yet reported the change in muscle strength of the intrinsic muscles over time. To further explore the recovery of muscle strength longitudinally in patients with nerve injuries data from measurements performed regularly (e.g. every three months after nerve injury) can be used.

Even though a period of two years after nerve injury is generally considered as the end point for recovery, recent studies have indicated that muscle strength can improve after an even longer period of time.[37]

6.3 Reliability of RIHM measurements in other patient groups and with inexperienced examiners

In this thesis we have studied the reliability of the RIHM only in patients with peripheral nerve injuries and determined the reliability of the RIHM with two experienced examiners only. Although we believe that performing these tests in different patient groups will result in few differences, this should be investigated.

Despite the fact that the clinician s experience in taking the measurements might also influence the measurement error, in grip and pinch strength measurements we found that this did not influence the reliability. This needs, however, to be confirmed in further studies.

Another issue is the time needed for a non-experienced therapist or physician to learn to use the RIHM in a reliable way. Although RIHM measurements might be slightly more difficult to perform than grip and pinch strength measurements, they are very similar to the measurement protocol of manual muscle testing regarding the point of pressure and methods of holding the hand of the patient.

7. Clinical implications

In the evaluation of peripheral nerve function, interpretation of manual muscle strength testing and grip strength measurements needs reconsideration. Although grip strength measurements do fulfil the requirements for quantitative measurement of the strength of the hand, they cannot differentiate between the intrinsic and extrinsic muscles. Strong grip strength does not necessarily imply strong intrinsic muscles. The results of the present study give more specific insight into the recovery of intrinsic muscle strength.

When choices are made about which technique provides the best results with regard to motor recovery of the muscles, an instrument such as the RIHM should be used.

Concerning the reliability of measurement instruments, we suggest to calculate the SDD/SD ratio. This ratio should probably need to be larger than 0.5 for an instrument to have acceptable SDDs, but this too needs further study.

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Summary

The hand has been called an extension of the brain, and the sensory and motor performance of the hand is based on adequate function of components in both the peripheral nerves as well as the central nervous systems. Damage to the nerves (e.g., injury, compression, infection [e.g. leprosy]) causes a loss of sensation and strength that may result in serious loss of hand function. According to Lundborg (2000) peripheral nerve lesions constitute one major reason for severe and longstanding impairment of hand function. He called the situation of nerve repair after injury frustrating because, although a nerve suture may be technically perfect and the rehabilitation carried out meticulously, the outcome is unpredictable and often disappointing.

The evaluation of muscle strength is, in combination with the assessment of sensibility, an important clinical method to determine ulnar and median nerve function. This information is valuable in decision-making concerning surgery (e.g. tendon transfers), therapy (e.g. splints), advice in work-related issues (e.g. safety to work with machines) and research issues (e.g. nerve repair technique). Concerning this latter topic, Trumble et al. (1995) noted that without extremely sensitive methods for monitoring the functional outcome of nerve regeneration, it will be difficult to identify those factors that may have small but additive beneficial effects and those that may have negative effects on nerve regeneration.

The main objective of the work presented in this thesis was to investigate the methods currently used to evaluate the motor domain of nerve function, i.e. manual muscle strength testing, and grip and pinch strength measurements. We questioned whether these methods give appropriate and sufficient information about the intrinsic muscle strength of the hand. Our hypothesis was that a dynamometer that provides quantitative data on the intrinsic muscle strength would provide more valuable information when monitoring the muscle strength of patients who have suffered nerve injuries of their arm.

Chapter 1 presents a general introduction to Manual Muscle Strength Testing (MMST), which was the first numerical system for the grading of muscle action. In 1954 the British Medical Research Council (MRC) specified a similar 0-5 scale in which grade 0 indicates total paralysis, grade 3 indicates that the limb can be moved against gravity, and grade 5 is normal. Several limitations of MMST are discussed: a) usually a muscle group is tested rather than just one muscle, b) the MRC scale is an ordinal one with disproportional distances between the grades, c) it is not appropriate for use in higher level muscle function (grades 4 and 5), and d) MMST is dependent on the examiner's experience to acquire reliable measurements.

Then we give a brief history of the development of dynamometers for the hand. In the past decades many different dynamometers have been introduced; for example, grip strength measurements using a dynamometer became popular and have been studied extensively.

Dynamometers for the measurement of intrinsic muscle strength of the hand are very important in clinical neurology for the evaluation of mononeuropathology and poly-neuropathology. One of the first to develop a dynamometer to measure intrinsic muscle strength was Mannerfelt. Later he manufactured a new device that was called the *intrins-o-meter.* Since then, several others have developed instruments mainly to assess the abduction of the thumb.

Chapter 2 describes the functional anatomy of the intrinsic muscles of the hand and its pathology, and discusses ways to assess muscle strength (both manual and instrumental) and the therapeutic options available.

Chapter 3 focuses on the first dynamometer to be utilised, which was a generic strain gauge instrument called the AIKOH. In a group of 24 patient with ulnar and/or median nerve injuries, several intrinsic muscle actions were measured to test reliability. There was an excellent level of reliability when comparing muscle strength between groups of patients. However, for individual patients, the calculated Standard Error of Measurements (SEM) and the Smallest Detectable Differences (SDD) for intra-observer and inter-observer values indicated that only relatively large changes in muscle strength could be confidently detected with this technique.

Chapter 4 Using the AIKOH, strength measurements were made of the lumbrical muscles of the index and middle finger in 12 patients with ulnar nerve injuries. The contribution of the interosseous muscles in maintaining the intrinsic position compared to the lumbrical muscles was measured and showed that the contribution of the lumbricals is only 12% compared to the non-involved hands.

Chapter 5 presents a study on grip and pinch measurements performed to gain more insight into the measurement error in strength measurements of the hand in general. The SEM and SDD of grip and pinch measurements were calculated in a consecutive sample of 33 patients with hand injuries. The aim was to determine indexes of measurement error for intra-examiner and inter-examiner measurements of grip and pinch force in patients, and to establish whether measurement error differs between measurements of injured and noninjured hands and between experienced and inexperienced examiners. Based on the SEMs and SDDs, in individual patients it was concluded that only relatively large differences in grip and pinch strength measurements could be adequately detected between consecutive measurements. Measurement error did not differ between injured and noninjured hands, or between experienced and inexperienced examiners. We proposed to judge the SDD proportional to the standard deviation, i.e. the SDD/SD ratio.

Chapter 6 describes the technical aspects of a dynamometer designed by the Instrument department of Erasmus University following our specific requirements: i.e. improved reliability to measure the muscle force of the intrinsic muscles, hand-held and portable, possibility to measure the opposition force of the thumb (opponens pollicis muscle), ergonomically designed grip, appropriate visual feedback of line of pull, and minimal errors from off-axis loading thus allowing measurement of axial forces only. This device is called the Rotterdam Intrinsic Hand Myometer (RIHM).

Chapter 7 A study was performed to assess the accuracy of the previously used industrial dynamometer (the AIKOH) and the new RIHM in applying the dynamometer perpendicularly in the frontal and transverse plane on the digit. The angle and place of application was determined using a three-dimensional videorecording technique. Differences between the two instruments, as well as measurement error and variance between two sessions, were calculated and compared. The ability to consistently position the instruments at the same reference point of the finger was also analysed. Less variation between the two sessions was found in positioning the RIHM dynamometer to measure muscle strength, and there was a smaller systematic error in the frontal plane.

Chapter 8 The reliability of the RIHM was investigated in 27 patients with ulnar and/or median nerve injury. For the two ulnar and two median nerve innervated movements the ICCs, SEMs and SDDs were calculated. The results showed that the ICC values and the SDD/SD ratios were very similar for intrinsic muscle strength measurements, and for grip and pinch strength measurements. The reliability of measurements with the RIHM is comparable to grip and pinch strength measurements and is acceptable to study the recovery and function of the intrinsic muscles of the hand in isolation.

Chapter 9 presents a study investigating muscle strength in 34 patients more than 2 years after ulnar and/or median nerve injury. The outcome of the muscle strength measured with four methods (manual muscle strength testing, grip and pinch strength measurements and the RIHM) were compared. Manual muscle strength testing and grip strength measurements showed a reasonable to good recovery, but measurements of the intrinsic muscles by means of the RIHM showed poor recovery of the intrinsic muscle strength. No correlation was found between the recovery of the intrinsic muscle strength and the grip strength measurements.
The RIHM dynamometer provides a more accurate clinical assessment of the muscle strength of the intrinsic muscles for two reasons. Firstly, with the RIHM intrinsic muscle strength is measured in

isolation, in contrast to grip and pinch strength measurements in which many (uninvolved) muscles are tested besides the intrinsic muscles. Secondly, because it provides quantitative results the RIHM measurements provide a more accurate clinical assessment compared with the manual muscle strength testing, especially in Medical Research Council grades 4 and 5.

Chapter 10 Finally, in this last chapter we address some issues related to the measurement of the muscle strength of the hand in a larger perspective: e.g. role of sensibility in strength measurements, relation between grip strength and intrinsic muscle strength, relation between intrinsic muscle strength and ADL, and reliability issues. Several of these questions need to be answered in order to find the best measurement method to determine the peripheral nerve function and, especially, the intrinsic muscle strength of the hand.

Nederlandse samenvatting

De hand wordt wel eens als het verlengstuk van de hersenen gezien, waarbij de sensorische (gevoel) en motorische (beweging) functies van de hand afhankelijk zijn van een adequaat functioneren van zowel de hersenen als de verbinding tussen de organen (hand) en de hersenen, n.l. de perifere zenuwen. Beschadiging van de zenuwen, bijvoorbeeld door een ongeval, compressie (bv carpaal tunnel syndroom) of infectie (bijvoorbeeld lepra) veroorzaakt een verlies van gevoel en spierkracht waardoor de handfunctie ernstig bedreigd kan worden. Volgens Lundborg (2000) zijn perifere zenuwbeschadigingen een belangrijke oorzaak van ernstig en langdurig verlies van de handfunctie. Hij noemt de situatie van zenuwherstel na een ongeval frustrerend omdat, ondanks het feit dat een zenuw chirurgisch technisch perfect gehecht kan zijn en er een optimale revalidatie heeft plaatsgevonden, de uitkomst toch onvoorspelbaar en vaak teleurstellend is.

Het evalueren van de spierkracht van de hand is, samen met het onderzoeken van de sensibiliteit, een belangrijke klinische methode om het functioneren van de ulnaris en medianus zenuwen te bepalen. Deze informatie is waardevol wanneer keuzes moeten worden gemaakt over operaties (bv pees transposities), therapie (spalk), advies over werksituaties (bv veiligheid om met machines te werken) en wetenschappelijk onderzoek (bv evaluatie van chirurgische hechttechnieken van zenuwen). Wat dit laatste onderwerp betreft schreef Trumble (1995) dat, zonder gevoelige methodes om de zenuwfunctie te bepalen, het moeilijk is om de factoren te identificeren die kleine maar waardevolle effecten kunnen hebben en factoren die negatieve effecten hebben op het herstel van de zenuwfunctie.

Het hoofddoel van dit proefschrift is om de bestaande meetmethodes die gebruikt worden om de zenuwfunctie te bepalen aan de hand van de spierkrachtmetingen, nader te onderzoeken. Beschikbare meetmethodes zijn het manueel spierkracht meten en knijp- en pincetkracht metingen. Wij betwijfelden of deze methodes wel de juiste zijn en voldoende informatie geven over de kracht van de intrinsieke spieren van de hand en veronderstelden dat een dynamometer die kwantitatieve data kan leveren over de intrinsieke spierkracht waardevollere informatie oplevert om de zenuwfunctie te bepalen

Hoofdstuk 1 Het eerste hoofdstuk van dit proefschrift is een algemene inleiding over het manueel spierkracht testen (MMST) welke een van de eerste systemen was, bedacht in 1954 door de Britisch Medical Research Council (MRC), om de kracht per spier te meten door middel van een 0-5 schaal. In deze schaal is graad 0 complete uitval, graad 3 is wanneer de vinger of duim een complete beweging kan maken zover als het gewricht dat toelaat en graad 5 is normale kracht. Deze MRC schaal heeft enkele nadelen: a) meestal wordt een spiergroep gemeten en is het geïsoleerd testen van een spier meestal niet mogelijk, b) de MRC schaal is een ordinale schaal met een ongelijke verdeling (graad 4 is niet 2x zo sterk als graad 2), c) in het gedeelte van de schaal rond graad 4 en 5 geeft het onvoldoende differentiatie, d) de betrouwbaarheid van het MMST is afhankelijk van de ervaring van de onderzoeker.

Hierna wordt een korte geschiedenis gegeven van de ontwikkeling van de dynamometers met betrekking tot spierkracht meting van de hand. In de laatste decennia zijn er verschillende dynamometers geïntroduceerd bijvoorbeeld de knijpkracht dynamometers, welke veel worden gebruikt.

Dynamometers om de intrinsieke spierkracht te meten kunnen belangrijk zijn in bijvoorbeeld de klinische neurologie om mono- en poli-neuropathologien te evalueren (van der Ploeg 1992). Een van de eerste die een dynamometer heeft ontwikkeld voor de intrinsieke hand spieren is Mannerfelt (1966) geweest. Later ontwikkelde hij een elektronische dynamometer die de intrins-o-meter werd genoemd. In de laatste decennia zijn er meerdere dynamometers ontwikkeld met name om de duimkracht te meten.

Hoofdstuk 2 In dit hoofdstuk beschrijven we de functionele anatomie van de intrinsieke spieren samen met de patho-kinesiologie ten gevolge van ulnaris en/of medianus uitval. Mogelijkheden van spierkracht meten (manueel en instrumenteel) en de verschillende therapie opties (preventie van complicaties, oefeningen) worden ook besproken.

Hoofdstuk 3 De eerste dynamometer die werd onderzocht om de intrinsieke spierkracht te meten was een generieke dynamometer; de AIKOH. Het onderzoek naar de betrouwbaarheid van de AIKOH metingen werd gedaan bij een groep van 24 patiënten met ulnaris en/of medianus zenuwletsels. De betrouwbaarheid indices zoals de Intraclass Correlatie Coëfficiënt (ICC), Standaard Error of Measurements (SEM) en de Smallest Detectable Differences (SDD) voor intraobserver en interobserver betrouwbaarheid toonden aan dat bij individuele patiënten alleen relatief grote veranderingen in spierkracht met zekerheid konden worden vastgesteld.

Hoofdstuk 4 Krachtmetingen van de lumbricales spieren van de wijs- en middel vinger werden uitgevoerd met de AIKOH bij12 patiënten met een ulnaris zenuw beschadiging. Het aandeel van de interossei spieren en de lumbricales om de vingers in de zgn. intrinsieke plus positie te houden werd vergeleken. Het aandeel van de lumbricales was slechts 12% vergeleken met de niet-aangedane hand.

Hoofdstuk 5 Om een beter inzicht te krijgen in de meetfout van krachtmetingen in de hand werd in een groep van 33 patiënten met een handletsel een onderzoek gedaan naar de intra- en inter-observer betrouwbaarheid van de knijp- en pincetkrachtmetingen van de hand. De meetfouten werden vergeleken tussen de aangedane en niet-aangedane hand en ook tussen de metingen van een ervaren en een niet ervaren tester. Gebaseerd op de Standaard Error of Measurements (SEM) en Smallest Detectable Differences (SDD) die we vonden werd geconcludeerd dat alleen relatief grote verschillen tussen twee opeenvolgde metingen van een individuele patiënt als werkelijke verandering konden worden beschouwd. Er werd geen verschil gevonden in de meetfout van de aangedane en niet-aangedane hand en ook niet tussen de ervaren en niet-ervaren tester. In dit hoofdstuk bespreken we ook welke criteria kunnen worden gebruikt om te beoordelen of de meetfout klein genoeg is. We stellen voor om de SDD te beoordelen in vergelijking met de Standaard Deviatie (SD) tussen personen met de zogenaamde SDD/SD ratio.

Hoofdstuk 6 gaat over het ontwerpen van de Rotterdam Intrinsic Hand Myometer (RIHM) voor het kwantitatief meten van de kracht van de intrinsieke spieren. In de literatuur zijn enkele dynamometers beschreven die de abductiekracht van de duim (antepostie) kunnen meten. Sommige van deze instrumenten zijn draagbaar, andere moeten op een standaard worden gemonteerd. Alle apparaten werken volgens de methode dat de dynamometer tegen de vinger en/of duim aan wordt geduwd. Geen van deze instrumenten kan de oppositie kracht van de duim meten.

Een instrument dat de spierkracht van de intrinsieke spieren meet heeft de volgende eisen: goede betrouwbaarheid en gevoeligheid voor verandering, draagbaar, ergonomische greep, goed zicht op de lijn waarin de kracht wordt geleverd waardoor deze zo min mogelijke afwijkt van de lijn loodrecht op de vinger. De Rotterdam Intrinsic Hand Myometer (RIHM) is ontworpen met deze eisen en meet door middel van een trekkracht via een lus die om de vinger/duim wordt gelegd. De RIHM heeft ook de mogelijkheid om de oppositiekracht van de duim te meten.

Hoofdstuk 7 Een onderzoek werd verricht naar de nauwkeurigheid van de loodrechte applicatie van de industriële dynamometer (AIKOH) en de nieuwe RIHM in het frontale en transversale vlak. De hoek waaronder met de dynamometer werd geduwd (AIKOH) en getrokken (RIHM) werd gemeten met een drie dimensionale video-recording techniek. Per meetinstrument werd de variatie in correcte (loodrechte) applicatie tussen meetsessies berekend en we beoordeelden of deze verschilde tussen de twee instrumenten. Ook de consistente plaatsing van de dynamometers op hetzelfde punt van de vinger en duim werd geanalyseerd. Met de RIHM dynamometer werd minder variatie gevonden tussen sessies in het correct plaatsen van de dynamometer en een kleinere systematische fout in het frontale vlak.

Hoofdstuk 8 De betrouwbaarheid van de metingen met de RIHM werd getoetst bij 27 patiënten met een ulnaris en/of medianus zenuw letsel. Per zenuw werden twee bewegingen getest en ICC, SEM, SDD en SDD/SD ratio's werden berekend. De resultaten lieten zien dat de betrouwbaarheid van metingen met de RIHM vergelijkbaar is met die van de knijp- en pincet-krachtmetingen De betrouwbaarheid van de RIHM is voldoende om het herstel van de intrinsieke spieren te kunnen meten.

Hoofdstuk 9 Resultaten van herstel van de spierkracht op de lange termijn werden onderzocht bij 34 patiënten met een ulnaris en/of medianus zenuw letsel. Resultaten van vier verschillende meetmethodes werden vergeleken: manuele spierkrachttesten (MMST), knijp- en pincet-kracht dynamometrie en de metingen met de RIHM dynamometer. Het herstel van de spierkracht van de intrinsieke handspieren, gemeten met de RIHM, was opvallend matig terwijl de knijpkracht op lange termijn goed herstelt. Metingen met de RIHM dynamometer leveren een nauwkeuriger bepaling van de spierkracht van de intrinsieke spieren om twee redenen. Ten eerste worden met metingen van de RIHM de intrinsieke spieren meer geïsoleerd gemeten in tegenstelling tot de knijp- en pincetkrachtmetingen waarbij meerdere spieren bv van de onderarm ook worden getest, (en ook de niet aangedane spieren). Ten tweede leveren de metingen met de RIHM kwantitatieve waarden op en zijn daarom nauwkeuriger dan de manuele spierkrachttesten met name op krachtniveaus van MRC schaal graad 4 (verminderde weerstand) en 5 (normale kracht).

Hoofdstuk 10 In het laatste hoofdstuk worden nog enkele zaken besproken aangaande het meten van de spierkracht van de hand zoals de invloed van de sensibiliteit, de relatie knijpkracht en de spierkracht van de intrinsieke spieren, de relatie tussen intrinsieke spierkracht en ADL, en betrouwbaarheid die van belang zijn voor het beantwoorden van de vraag welke meetmethodes het meest geschikt zijn om de perifere zenuwfuncties te bepalen, met name de spierkracht van de intrinsieke spieren in de hand.

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Curriculum Vitae

The author was born in Johannesburg (South Africa) and at the age of 5 moved with his family to the Netherlands. After primary school in Reeuwijk (Johannes Calvijn MAVO) and secondary schooling in Gouda (Christelijk Lyceum), a vocational advisor suggested he should study physiotherapy. These studies were started in 1977 at the School for Physiotherapy (SUPA) in Utrecht.

His first job as a physiotherapist was at private physiotherapy clinics (owned by Mr. Huib Pieneman) in Gouda and Stolwijk where he worked from 1982 to1984. In 1985 he and his wife, Hilde, joined The Leprosy Mission International (TLMi). After one year at the London Bible College, Summer Institute of Linguistics, three months of leprosy training in India, and seven months attending a language school in Bangkok, they moved to Chiangmai (the second largest city in Thailand) to work at the McKean Rehabilitation Center. He was head of the Physiotherapy department there from 1986 to 1992. During this period he also lectured at the school for Physio- and Occupational Therapy in Chiangmai.

After returning to the Netherlands in 1992 he worked on a part-time basis at the Nederlands Paramedisch Instituut (NPI) and at the Rehabilitation department of the Medisch Centrum Alkmaar. He also worked as a consultant for TLMi and the Netherlands Leprosy Relief organisation.

From 1994 onwards he was employed as a Hand Therapist at the department of Rehabilitation Medicine of the Erasmus MC Rotterdam. After receiving a grant from the local Revolving Fund, a research project was started in 1999 that has culminated in the work presented in this thesis.

Since 2000 the author has also has been co-ordinating a hand therapy course (Praktijk Opleiding Hand Therapie) at the Erasmus University Hospital Rotterdam.

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