Measuring Hand Strength in Children

Het meten van handkracht bij kinderen

Ties Molenaar

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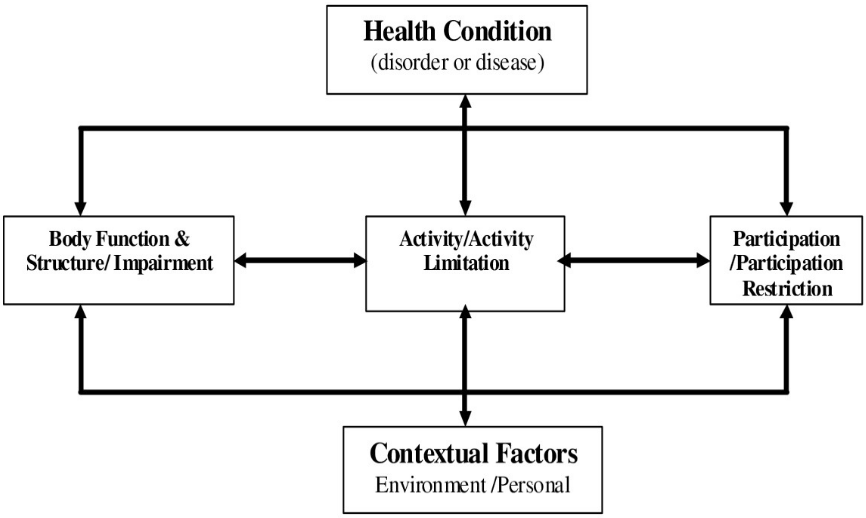
Contents

Chapter 1

Introduction

When treating a patient with specific hand conditions, such as patients with a trauma, with neurodegenerative diseases or with congenital malformations, the goal is generally to improve the patient's hand function. Hand function measurements are therefore often performed to evaluate treatment outcome for interventions aimed at improving hand function. But what is hand function? Hand function is a rather broad term conventionally used to describe different aspects of the functioning hand. Since the term is so broadly defined, however, it might be better to describe hand function more systematically. According to the World Health Organization, the systematic description of someone's health condition is comprised of several attributes. These attributes are described in the International Classification of Functioning, Disability and Health (ICF). Besides contextual factors like environment or personal factors, the three major attributes are Function & Structure / Impairment, Activity and Participation (Figure below).



Concerning the first attribute in the ICF model: **Functions, Structures and Impairments of the body**, the World health organization describes them as follows:

- Body Functions are physiological functions of body systems (including psychological functions).
- Body Structures are anatomical parts of the body such as organs, limbs and their components.
- Impairments are problems in body function or structure such as a significant deviation or loss.

The next attribute of the ICF-model as defined by the World Health Organization is **Activity/Activity Limitations**:

- Activity is the execution of a task or action by an individual.
- Activity Limitations are difficulties an individual may have in executing activities.

The final attribute is **Participation / Participation Restriction**:

- Participation is involvement in a life situation.
- Participation Restrictions are the problems an individual may experience in involvement in life situations.

The contextual factors such as the Personal factors are not described in the ICF model. However, the Environmental factors are defined as follows:

- Environmental factors make up the physical, social and attitudinal environment in which people live and conduct their lives (1).

When we look at the current clinical practice for measuring the above mentioned aspects of the ICF-model, there are specific assessments methods for all domains that apply to the hand. For Body Function & Structure / Impairment of the hand, there are various methods to measure aspects such as joint mobility, joint stability, pain, edema, sensibility and strength. For the hand, Activity actions that are generally scored are items on manipulating objects such as opening a jar or closing a blouse with little knobs (2-4). Participation in normal day life is often measured with more generalized questionnaires on aspects such as work status and quality of life (5).

As emphasized before outcome of body function can be measured in different ways. Our main interest for this thesis was hand strength measurements as part of hand function in children both for the normal child as for the child with a congenital hand malformation. An explanation of the use of strength measurements of the hand in general precedes strength measurements in the child for better understanding.

Measurement of maximum strength is generally used in medicine to study the function of the complete neuromuscular system. For example, in carpal tunnel syndrome, hand muscle strength is often used to measure motor function of the median nerve and atrophy of the thenar muscle (6). After a ulnar or median nerve injury, muscle strength can be used to study motor recovery (7) while in neuromuscular diseases such as Charcot Marie Tooth, repeated measurement of hand strength over time can be used to monitor disease progression of the neuromuscular system (8-9). It should be noted that while in some situations, such as in sport sciences, the interest is specifically on how strong the muscle actually is (10), in many clinical situations maximum muscle strength is used as an indicator of the quality of the neuromuscular system and the development of this system over time or after intervention.

To assess capacity of the neuromuscular system, measuring maximum strength is not the only option. For example, for patients, it may be more important to have sufficient control of the strength level and to be able to apply a specific force in the direction that is needed for a specific task. Therefore, some alternatives measures of muscle function have been developed. For example, studies have evaluated the ability of patients to track specific patterns on a computer screen by modifying the force level (5) while others have designed tasks that combine creating specific force levels as well as controlling the direction of these force levels (11). In addition, a number of studies have focused specifically on neuromuscular endurance and fatigue, which can, for example, be important in elderly people or patients with neuromuscular diseases (12). However, until today, assessment methods of force control, fatigue, endurance are relatively complex and time consuming and have shown to be less reliable than measuring maximum muscle force (3). Therefore, in clinical practice as well as in research, measurement of maximum strength is most generally used as an indicator for the functioning of the neuromuscular system since it is easily instructed and performed and since results can be easily compared between sessions and among peers. Furthermore maximum strength is more reliable to measure than control and fatigue tasks that have been studied until today.

There are a number of different techniques or approaches towards measuring maximum strength. Muscle strength can be measured either isokinetically where speed and resistance stay the same throughout the measurement (13) or isometrically where the joint is in a fixed position (14). In addition, some systems such as the Biodex measure a joint torque, while others measure a force or the strength during a specific task such as gripping or pinching an object (15).

Measurement of maximum strength is also the focus of this study. Even though the magnitude of hand strength a person can produce may not be relevant for daily functioning, several studies suggest a positive correlation between hand strength and hand activity / participation questionnaires like the DASH (3, 16). The specific relations between strength and activity may depend on specific pathology. For example, for hand strength, in a study from our department on patients with Charcot–Marie–Tooth (CMT) disease, we related hand muscle strength to activity and found that intrinsic muscle strength was more strongly related to fine activities of the hand and fingers while grip and wrist strength were more strongly related to the DASH, which is a more global assessment of the upper extremity activity (8).

Hand strength can be assessed with different instruments that measure different grasping functions such as tip pinch, key pinch, tripod pinch and grip strength. These strength measurements are functionally relevant since they measure important daily tasks. However, they have the disadvantage of involving a number of different fingers, joints and muscles at the same time. Since appropriate instruments were traditionally lacking, measuring strength of individual fingers or thumb is generally not performed in everyday practice even though interventions are often aimed at strengthening specific fingers or thumb. Therefore this research covers not only grip and pinch measurements but also strength measurements of individual fingers or thumb.

For the grip and pinch measurements, we used and compared well-known instruments such as the Martin Vigorimeter for grip pressure, a grip strength dynamometer similar to the well known Jamar dynamometer and a pinch dynamometer. For measuring individual finger strength or thumb strength we used a newly developed instrument: the Rotterdam Intrinsic Hand Myometer (RIHM). The RIHM is a device capable of measuring muscle strength of individual fingers and the thumb and therefore suitable for directly assessing intrinsic muscle strength or, for example, thumb opposition after a tendon transfer.

At the Erasmus MC in Rotterdam, the department of Plastic & Reconstructive Surgery and the department of Rehabilitation Medicine collaborate when treating patients with hand problems. A special focus is aimed at patients with congenital hand malformations. Many of these children receive their first hand-related intervention soon after birth, so that they can quickly adapt and develop their hand function as normal as possible. Because patients treated for congenital malformations are therefore often young and treated in the first few years of their lives, measuring hand strength in these young children is highly relevant for developing and evaluating treatment outcome.

Measuring hand strength in young children has a number of specific problems. The first topic that we dealt with was choosing the instrument and measurement protocols with the best reliability in children and establishing the effect of age of these children on reliability. The physical process of growth may influence reliability of strength measurement. In addition, in young children, the ability of children to understand and perform a strength task may also influence reliability. To our knowledge, at the start of this research, a comparison of the reliability of the different grip strength instruments in children had not been performed. Only one study reported reliability of a grip strength dynamometer in children (17). However, the instrument assessed was different than the one used in our daily clinical practice. Therefore, a further comparison of reliability between different instruments was needed. Furthermore, reliability of grip strength measurements was only described for children between 6 to 11 years old (18) an in adults and elderly populations(19-21).

Beside reliability another important aspect for using hand strength measurements in children is having correct reference values. These reference values for children are needed as a comparison, especially when both hands are involved. To our knowledge, reference values in literature were mostly reported for adults and elderly. Only three studies reported reference values for a grip strength dynamometer in children (22-24). In one of these studies the age interval ended at the age of 5 (starting at 3 years); the other two studies started with children of 5 years and older. In addition, all reference values for hand strength were described in a table-format and depending on the specific study; grip strength was described as a function of age-range, gender and hand-dominance. With these different reference values it was therefore difficult to study progression or decline in strength of the patient over time, warranting the development of new reference values.

An innovative new technique for measuring hand strength is the RIHM, which was designed at the Erasmus Medical Center in Rotterdam to measure the strength of the individual fingers and thumb in different directions. At the start of this study, however, the RIHM had never been applied in children. Therefore, it was unknown if the instrument was reliable in children. In addition, for use of this instrument in children, appropriate reference values were lacking.

Finally, in this research we focused on applying the traditional grip and pinch strength measurements as well as the newly developed RIHM in a group of patients with a hypoplastic thumb. Hypoplasia of the thumb refers to a spectrum of clinical abnormalities ranging from a slightly small digit to loss of musculoskeletal elements in the thumb unit, to complete absence (or aplasia) of the thumb. It is a component of radial dysplasia, and is commonly seen either alone or in conjunction with other conditions associated with radial longitudinal deficiency (25). We applied different hand strength measurements in these patients in order to compare the differences between instruments and illustrate the added value of using individual thumb- or finger strength measurements besides regular grip or pinch strength measurements.

Aims and Outline

The research presented in this study focuses on hand strength measurements in children. The first aim of this research was to establish reliable methods for measuring hand strength in children. The second aim was to generate reference values for these methods. The third aim was to apply the full spectrum of hand and finger strength measurements in a clinical setting and compare the added value of the different instruments.

Chapter 2 compares the reliability of two well-known grip strength dynamometers: The Martin Vigorimeter and a Jamar-like grip strength dynamometer in children from a primary school in Rotterdam. The chapter explores the effect of age on the reliability of both dynamometers.

Chapter 3 further investigates the reliability of the most reliable grip strength dynamometer reported in chapter 2. In order to cope with several factors that possibly could influence or improve the reliability of measuring grip strength in children we developed three specific test protocols. We specifically compared the standard method with two other protocols where the weight of the instruments was either reduced or where visual feedback on task performance was added on computer screen.

Chapter 4 describes reference values in children from 4 – 12 years using the same grip dynamometer as used in the previous chapters. To incorporate the effect of growth and neuromuscular maturation on grip strength we developed easy to interpret growth curves. These growth curves are similar to those curves used in infant welfare centers around the globe to follow their length or weight over time. In our case we used the reference data on grip strength to plot a curve that could predict grip strength as accurate as possible over time.

Chapter 5 focuses on a new instrument for assessing hand strength: the Rotterdam Intrinsic Hand Myometer (RIHM). The RIHM is a dynamometer that is capable of measuring strength of individual fingers, by measuring strength over an individual joint and the associated muscle group. This instrument was adjusted for use in children and the reliability of the RIHM in children was evaluated.

Chapter 6 applies the same logic and methodology of using reference values in children for the RIHM measurements as described in chapter 4 for grip strength. The RIHM was used to assess five different motor skills of the hand, 3 involving the thumb and 2 from the index finger and little finger. Growth diagrams were developed, facilitating an intuitive approach on using reference values to follow progress of individual patients over time.

Chapter 7 describes a study where the different methods for measuring hand strength are applied in children with thumb hypoplasia. The study specifically evaluated the added value of RIHM measurements in addition to the commonly used grip and pinch strength dynamometer.

Finally chapter 8 accumulates all the information from the previous chapters and uses the data to draw several important conclusions. The study is put in perspective to existing research and solutions, limitations and possible future implementations are discussed.

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Age-specific reliability of two grip strength dynamometers when used by children. - American Journal of Bone & Joint Surgery: 2008;90(5):1053-9

Chapter 2

Age-specific reliability of two grip strength dynamometers when used by children

Abstract

Background: Grip strength is a key parameter in the assessment of hand function. Instruments often used, the Jamar dynamometer and Martin Vigorimeter, have good validity and reliability in adults. Grip strength measurements are often performed in children with hand disorders. However, reliability of these measurements is unknown in children under 12 years. In addition, it is not clear whether reliability differs between younger and older children. Purpose of this study was to establish test-retest reliability for different age groups and to determine which instrument is the most accurate to use.

Methods: 104 children from a primary school were included. Subjects were divided into three groups: 4-6, 7-9 and 10-12 years of age. Grip strength was measured for both hands with the Lode dynamometer (equivalent to the Jamar dynamometer) and with the Martin Vigorimeter. For all measurements, the mean of three maximum voluntary contractions was recorded. A retest was performed with a mean retest interval time of 29 days.

Results: Intra-class correlation coefficients (ICC's) of the Lode dynamometer for the total group were 0.97 (95% confidence interval 0.95-0.98) for the dominant hand, and 0.95 (0.92-0.96) for the non-dominant hand. For the Martin Vigorimeter the ICC's were: 0.84 (0.77–0.89) for the dominant hand and 0.86 (0.80–0.90) for the non-dominant hand. For the different age groups, ICC's were lower compared to the total group, due to a lower between-subject variation The normalized smallest detectable difference (SDD) for the Lode dynamometer was approximately 25% and for the Martin Vigorimeter 31%.

Conclusion: oth Lode dynamometer and Martin Vigorimeter are reliable instruments to measure grip strength in children (<12 years), however the Lode dynamometer has higher ICC's indicating a better test-retest reliability. Comparing SDD's, the Lode dynamometer is a more accurate instrument. 4-6 year old children have relative high normalized SDD of 35% compared to the 20% of the 10-12 year olds, which is close to SDD's found in adults.

Introduction

Grip strength is used to measure dysfunction and treatment outcome in different disorders such as trauma, congenital problems and degenerative diseases. Instruments frequently used are the Jamar dynamometer or equivalent devices such as the Lode dynamometer (Figure 1) and the Martin Vigorimeter (Figure 2). Although both instruments measure grip strength, Jamar-like dynamometers quantify isometric force in Newton, while the Martin Vigorimeter measures spherical grip strength in kilopascal using a rubber balloon.(1, 2)

Figure 1,
Child (age 4) with
Martin Vigorimeter

Figure 2 ,
Child (age 4)
with Jamar-like
dynamometer
(Manufacturer: Lode
B.V., Netherlands)

Both instruments are used to measure grip strength in children. However Jamar-like dynamometers are larger and heavier instruments and may therefore be more difficult to use in children. Furthermore the Martin Vigorimeter has special designed smaller bulbs for children.(3, 4) For both instruments, normative data have been reported for adults.(3, 5, 6) In addition, for children, normative data are reported for the Jamar dynamometer (> 5 years)(7, 8) and for the Martin Vigorimeter (3-6 years).(2, 9) However, to our knowledge, a direct comparison of both instruments in children has never been performed.

It is not clear whether a Jamar-like Dynamometer or the Martin Vigorimeter is more suited to measure hand strength in children, because a comparison of reliability of these instruments has only been performed in adults and elderly. In addition, it is not clear whether the reliability of the instruments depends on the age of children. In most studies, the authors have investigated reliability for children in general, instead of subdividing them into different age groups.(10-13) It might be argued, however, that aspects such as the size of the hand, the ability to understand the task or the limited attention span of younger children may lead to less consistent performance and therefore a decreased reliability. In addition, a similar difference between test and retest (expressed in newtons or kilopascals) may have a bigger relative impact on the error for weaker children than on the error for stronger children when that error is expressed as a percentage of the children's maximum strength. For example, a measurement error of 20 Newton has a larger impact in a child with 40 Newton grip strength (50% error) than in a child with 200 Newton grip strength (10% error).

The first aim of this study was therefore to directly compare reliability of a Jamar-like and the Martin Vigori dynamometer to measure hand strength in children (4-12 years old) and the second aim was to study the difference in reliability of grip strength measurements between different age groups.

Materials and Methods

Patients Sample Characteristics

After approval of the ethical committee and after informed consent of their parents, children from a primary school were approached for participation. A total of 104 children from a primary school participated in this study. A questionnaire was used to ask the parents about hand dominance and any known upper extremity problems that could influence hand strength. All children with any upper extremity problems were excluded from the tests. Subjects were divided into three groups ranging from 4-6 and 7-9 and 10-12 years of age (Table 1). Of all children, 88% were right hand dominant.

Table 1, Number of participants divided among age groups and gender.

Age (years)	**Boys**	**Girls**	**Total**
4-6	12	18	30
7-9	16	23	39
10-12	17	18	35
Total	45	59	104

Strength Measurements

Grip strength was measured for both hands using an electronic Jamar-like Dynamometer (Lode dynamometer, Lode B.V., Groningen, the Netherlands) and the Martin Vigorimeter. During measurements all children were seated in appropriately sized chairs in the position suggested by the American Soc iety of Hand Therapists (ASHT): subject sitting, shoulder abducted, elbow in 90 degrees flexion, and wrist in neutral position.(14) The Jamar-like dynamometer was only used with the handlebars in position 2. Additionally, for the Martin Vigorimeter, the medium bulb was used and the subject's forearm was neutrally resting on the table with the wrist in 0^{o} to 30^{o} of extension.(9)

The same two instruments were used throughout the tests. The electronic Jamar-like dynamometer was reset prior to every measurement. The Martin Vigorimeter was newly purchased just before initiating our tests. All measurements were performed by the same researcher (HMM). The tests were undertaken in randomized order. No other persons besides researchers (HMM & JMZ) and child were present in the room during testing. Subjects were instructed before each test with the words: "Squeeze as hard as you can!" For both instruments, the mean of three maximum voluntary contractions (MVC's) was recorded for each hand. A retest was performed under the same conditions with a mean retest interval time of 29 days (range: 3-56 days).

Statistical Methods

Test-retest reliability of the measurements was visualized using Bland-Altman plots.(15) In addition, the following indexes were calculated:

- Intraclass correlation coefficient (ICC), which is the ratio of variance of interest (between-subject variance) over variance of interest and error variance (between-subject plus within-subject variance).(16)
- Standard error of measurements (SEM), which is calculated as the square root of the error variance.(17, 18) Although ICC and SEM are related, they define different properties. The magnitude of the ICC indicates the ability to discriminate among subjects, whereas the SEM calculates the error in measurement in the original unit of measurement.(16, 17, 19-21)
- Smallest detectable difference (SDD), which is the amount of change between tests that is needed to detect a real difference in a subject's performance. For a 95% confidence level, the SDD is calculated: 1.96 x √2 x SEM.(20) When two measurements differ more then the SDD, it can be concluded that the change represents a real (non-error) change in strength.(17)
- Normalized SDD, which is the above-mentioned SDD expressed as a percentage of the MVC. Without normalization, the SDD of both dynamometers are not directly comparable because of the different units of measurement (N and kPa). However, when expressed as a percentage of the MVC, the outcomes are comparable. In addition, the normalized SDD is a measure that is interpretable from a clinical point of view. For example, a SDD of 25% indicates that the result of the follow-up test should differ from that of the first test by at least 25% in order to demonstrate a real (non-error) change in grip strength.

Results

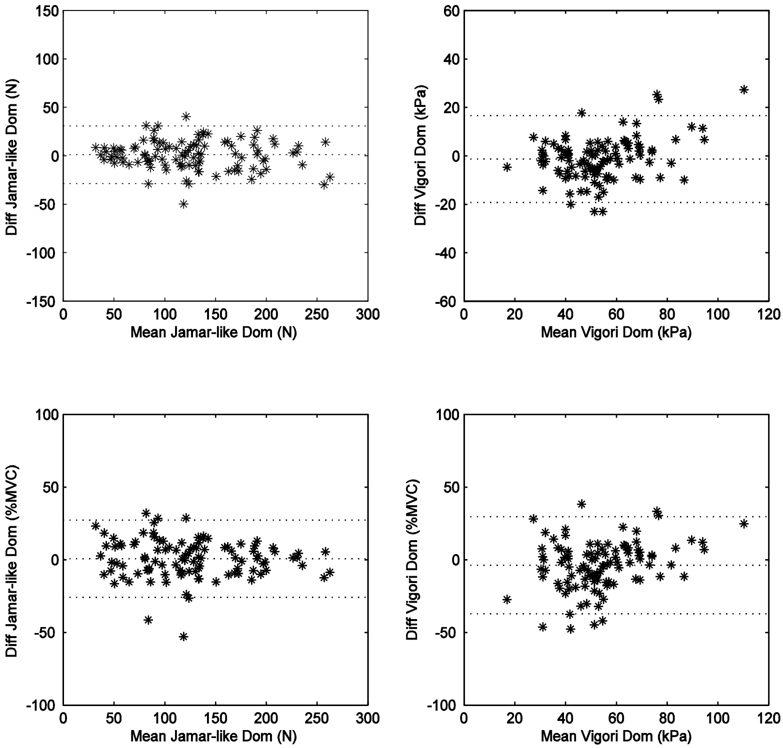
For the Jamar-like dynamometer, ICC for the total group was 0.97 for the dominant hand and 0.95 for the non-dominant hand (Table 2). For the Martin Vigorimeter, ICC's were lower: 0.84 for the dominant hand and 0.86 for the non-dominant hand. The 95% confidence intervals of ICC's of both instruments do not overlap for the whole age group and for most subgroups, indicating that the ICC's for the Jamar-like dynamometer are significantly higher than for the Martin Vigorimeter. Comparing the different age groups for both instruments, no clear relation was found between age and ICC.

Table 2,Intraclass Correlation coefficients (ICC's) for Jamar dynamometer and Martin Vigorimeter with the 95% Confidence Intervals (C.I.)

Age (years)	**Hand**	**Jamar**	**95% C.I.**	**Vigori**	**95% C.I.**
4-6	Dominant	0.91	0.81-0.96	0.76	0.55-0.88
	Non-dominant	0.73	0.50-0.86	0.79	0.61-0.90
7-9	Dominant	0.78	0.62-0.88	0.47	0.17-0.69
	Non-dominant	0.79	0.64-0.88	0.55	0.29-0.74
10-12	Dominant	0.92	0.85-0.96	0.70	0.48-0.83
	Non-dominant	0.82	0.66-0.90	0.70	0.49-0.84
Total	Dominant	**0.97**	0.95-0.98	**0.84**	0.77-0.89
	Non-dominant	**0.95**	0.92-0.96	**0.86**	0.80-0.90

The Bland-Altman plot of the mean versus the difference of the maximum voluntary contraction (MVC) of test and re-test shows that data are evenly distributed around the zero-difference line (Figure 3). The plots illustrate similar differences between test and retest for the weaker (mostly younger) and stronger (mostly older) children when expressed in Newton or Kilopascal. (15) However, measurement error is higher in weaker children as compared to the stronger children when expressed as a percentage of the MVC. This effect was similar for both dominant and non-dominant hands.

Figure 3, Upper half: Scatter plot of the mean maximum voluntary contraction for the dominant hand using a Jamar-like and Martin Vigori dynamometer during the two sessions versus the difference between the mean voluntary contractions (MVC). Lower half: Scatter plot of the mean maximum voluntary contraction (MVC) for the dominant hand using the Jamar-like and Martin Vigori dynamometer during the two sessions versus the percentage in difference between the two sessions. The errors expressed in Newton or Pascal do not seems to differ between weaker and stronger children. However, when the error is expressed as a percentage of the MVC, measurement error has a bigger affect in weaker children, indicated by the larger differences in the left part of the graph.



The effect of age on mean, SEM, SDD and normalized SDD for both instruments is shown in Table 3. The non-normalized smallest detectable difference increased with age. However, the older children also had greater grip strength, so the smallest detectable difference decreased with age. Comparing both instruments, the Jamar-like dynamometer has a lower normalized SDD (approximately 25% MVC for both hands) in contrast to the Martin Vigorimeter (approximately 31% MVC for both hands). This difference is largest for the oldest age group (20% MVC for the Jamar-like dynamometer and 31% MVC for the Martin Vigorimeter.

Table 3, Mean of maximal voluntary contractions for Jamar dynamometer (in Newton) and for Martin Vigorimeter (in kilopascal). Standard Error of Measurement (SEM) and Smallest Detectable Difference (SDD), absolute and in percentage of the mean strength.

		Jamar				**Vigori**			
Age (years)	**Hand**	**Mean** (N)	**SEM** (N)	**SDD** (N)	**SDD** (%)	**Mean** (kPa)	**SEM** (kPa)	**SDD** (kPa)	**SDD** (%)
4-6	Dominant	66.9	6.7	18.4	27.6%	38.7	4.9	13.5	34.9%
	Non-dominant	62.0	7.9	22.0	35.5%	37.6	4.6	12.6	33.6%
7-9	Dominant	118.7	12.2	33.9	28.5%	54.7	5.7	15.7	28.7%
	Non-dominant	110.8	10.3	28.4	25.6%	54.6	5.3	14.7	26.9%
10-12	Dominant	184.6	11.3	31.2	16.9%	67.9	7.6	21.1	31.1%
	Non-dominant	174.7	14.6	40.5	23.2%	67.7	7.5	20.8	30.8%
Total group	Dominant	125.9	10.5	29.2	**23.2%**	54.5	6.3	17.5	**32.2%**
	Non-dominant	118.6	11.5	32.0	**27.0%**	54.1	5.9	16.4	**30.4%**

Discussion

The first aim of this study was to directly compare the reliability of a Jamar-like dynamometer and Martin Vigorimeter in children between 4 and 12 years of age. The second aim was to study the effect of age on reliability of strength measurements in children. We compared both instruments in terms of reliability, because this criterion can be objectively compared. Even though reliability of both Jamar-like dynamometers and Martin Vigorimeter has been evaluated in different populations(4, 10, 22-28), it has never been compared. For example, while Fike et al. found a high correlation between both instruments in adults, they did not compare reliability.(29) Desrosiers et al. reported that both instruments correlated highly with hand anthropometric data, but also did not compare reliability.(30)

Some limitations of our study should be noted. First, this study was performed in children without upper limb impairments. Therefore, no conclusions can be drawn on the reliability in children with impairments. In addition, due to practical reasons, time between test and retest was relatively long in some of the children, ranging between 3-56 days with an average of 29 days. Figure 3, however, indicates there was no overall increase in strength of the group, suggesting that overall the children did not gain strength between test and retest.

Although smaller children needed a wider grip, resulting in a more distal placement of the finger on the Jamar-like dynamometer in position 2, all children were still able to perform a MVC.

In this study we found that both instruments had good to excellent reliability. However, ICC's for the total group of the Jamar-like dynamometer were significantly higher than for the Martin Vigorimeter. For the whole group, the ICC's of 0.95 to 0.97 for the Jamar-like dynamometer are in line with ICC's of 0.90 or higher reported in previous studies for adults and children.(21-27) Merkies et al.(2000) found inter observer and intra observer ICC's of 0.95-0.97 for adult patients with polyneuropathies using the Martin Vigorimeter.(11) This ICC is higher than in our study, which may be related to a wider range in age (14 – 84 years) and grip strength in their population, resulting a higher between-subject variation. With a similar difference between test and retest (within-subject variation), more between-subject variation will result in a higher ICC's.

When designing this study, we expected that the Martin Vigorimeter would be more reliable in children than Jamar-like dynamometer for testing grip strength in children because its bulb is lighter and softer than the handlebar of the Lode dynamometer. However, the Jamar-like dynamometer proved to be a more reliable instrument for testing grip strength in children. In addition to a higher ICC, the Jamar-like dynamometer also had a smaller normalized SDD (25%) compared to the Martin Vigorimeter (31%), indicating a smaller relative measurement error. Overall, our data suggest that Jamar-like dynamometers are a more reliable instrument to measure grip strength in children.

The second aim of this study was to determine reliability in different age groups. For the ICC's, we found no clear effect of age. Since ICC's are not only determined by the measurement error but also by the between-subject variation, the ICC values are difficult to compare across age groups.

The same influence of between-subject variation on the ICC values may also explain why all three age groups had lower ICC's than the ICC of the total group. The effect of age on the measurement error of both instruments was therefore also visualized for all individual subjects in Figure 3. The upper half of Figure 3 indicates that the measurement error in the original units (N or kPa) is not clearly different between stronger and weaker children. However, when the test-retest difference was normalized, it represented a much bigger percentage of the maximum voluntary contraction of the weaker children than of the stronger children. Thus, the error of measurement is larger in the less powerful children (lower half of Figure 3). The same effect is seen in the SEM and SDD. When expressed in the original units, increasing SEM and SDD are found with increasing age. However, when the smallest detectable difference was expressed as a percentage of the maximum voluntary contraction, it decreased with increasing age, indicating higher reliability with increasing age.

Although our study clearly indicates the effect of age on reliability of grip strength measurements, it remains more or less arbitrary to conclude on a minimal age for performing reliable grip strength measurements. Since normalized SDD values may be a more clinically relevant outcome measure than ICC and non-normalized SDD, we have compared our normalized SDD values with literature on adult grip strength reliability. For adults, several studies reported normalized SDD's of 17 to 20 percent for the Jamar Dynamometer.(21, 27, 31) The normalized SDD's in the present study for the oldest group (10-12 years) are therefore similar to healthy adults. With decreasing age, however, the reliability decreases and effect of measurement error increases effect. Whether grip strength measurements are still useful for the youngest children depends on the experimental situation. For example, to detect change in the strength of an individual young child after an intervention or therapy, the change must be large enough to exceed measurement error, whereas in research studies comparing different groups, grip strength measurements may still be useful even for the youngest children tested (four to six years of age).

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Visual feedback and weight reduction of a grip strength dynamometer do not increase reliability in healthy children - Journal of Hand Therapy:2010;Mar 18

Chapter 3

Visual feedback and weight reduction of a grip strength dynamometer do not increase reliability in healthy children

Abstract

Study design:

Test-retest reliability study on grip strength in children.

Introduction:

Measuring grip strength in children is difficult because of the weight and size of the instrument, brief attention span, and possible lack of task understanding. Therefore, adaptations to the measurement protocols to improve reliability would be very important for research and clinical evaluation.

Purpose:

In this study, we compared the reliability of a grip strength dynamometer using three different protocols.

Methods:

Test-retest reliability of the American Society of Hand Therapists protocol in 104 healthy children (4-12 years) was compared to the reliability in 63 healthy children of a visual feedback protocol and a suspension protocol reducing weight of the instrument.

Results:

For the total group, intraclass correlation coefficients for the dominant and nondominant hand were 0.95-0.97 for all protocols, indicating that all three protocols were reliable.

Conclusion:

No statistically significant difference was found between the reliability of the different protocols but the suspension protocol produced small but significantly higher force levels.

Introduction

Grip strength is often used to measure dysfunction caused by trauma, congenital problems, or degenerative diseases.(1) Grip strength measurement devices frequently used to assess grip strength are the Jamar dynamometer (Jamar, TEC, Clifton, NJ, USA) or equivalent devices such as the Lode dynamometer (Lode B.V, Groningen, The Netherlands). These dynamometers have been proven to be reliable in various populations.(2-7)

Measuring grip strength in children is difficult for several reasons. Most instruments used to measure grip strength are designed for adults and are therefore relatively heavy and large for use by children. Furthermore, a child's brief attention span, a possible lack of understanding of the task or varying levels of motivation to perform a maximum force effort at each trial can also influence the reliability of grip strength measurement in children.(8) In addition, absolute measurement error has a relatively large effect in children because of their low grip strength.(9) Therefore a different approach to measuring hand strength in children is needed.

The reliability of grip strength measurement in children might be improved by several changes in the measurement protocol. For example, in adults with Charcot-Marie-Tooth disease, suspension systems have been used to compensate for the weight of the apparatus.(10) Providing visual feedback for the patient during assessment may also contribute to a more reliable outcome. Several studies in adults have shown that adding visual feedback during strength measurements provides more consistent and potentially higher force output.(11-13) Visual feedback can often be supplied by modern electronic dynamometers that are linked to a computer and are equipped with software for visualizing force exerted by the subject. Viewing a real-time display of the strength that a subject exerts during testing could make the evaluation more interesting or more comprehensible to children. For these reasons the reliability or force output could potentially be improved by using weight reduction and visual feedback in children. However, until today, the beneficial effects of this visual feedback on hand strength measurements have not been studied in children. To establish the effect of suspension and visual feedback on the measurement of grip strength, we compared 3 different measurement protocols. The first aim of this study was to compare the reliability of those 3 protocols in measuring grip strength in children (age range, 4-12 years). The effects of each protocol on the amount of force exerted by each subject during testing were also compared.

Materials and Methods

Subjects

After this study had been approved by the Ethical Committee of the Erasmus MC, University Medical Center and the parents of potential subjects had provided informed consent, local primary school children without upper limb impairment were approached for participation. Hand dominance and upper extremity problems that could influence hand strength were determined by evaluating parents' responses to a custom made questionnaire on the parents' opinion of their child's hand dominance and on the history of possible upper extremity problems. Children with a history of upper extremity trauma or abnormalities were excluded. Children with other conditions that could possibly affect hand function, such as attention deficit disorders or neuro-muscular problems, were also excluded. In this study, we combined data from an earlier study (GRIP1-study)(9). From the GRIP1 study, we obtained data from 104 children on reliability of the American Society of Hand Therapists' protocol. We collected additional data on reliability of the Visual Feedback and Suspension protocols from 63 children from the same preliminary school (GRIP2-study). Some children from the GRIP1 study also participated in the GRIP2 study. They were, however, seen as independent samples because of the large time difference of approximately one year between both studies. To compare absolute strength we used unpublished data collected during the GRIP1 study, where we used all three protocols in 128 children to measure grip strength. All subjects were divided into 3 groups according to age: 4 to 6 years, 7 to 9 years, or 10 to 12 years. Of all the children studied, 94% were right-handed (Table 1).

Strength measurements

A grip strength dynamometer (Lode dynamometer, Lode BV, Groningen, The Netherlands) was used in 3 measurement protocols (Figure 1). In the first protocol the dynamometer was used as recommended by the American Society of Hand Therapists (ASHT): The subject sat with the shoulder abducted and the arm at the side of the body, the elbow flexed in a 90-degree angle, and the wrist in a neutral position.(14) Data on reliability for the American Society of Hand Therapists protocol (reported in our previous study GRIP1-study, (9)) were used.

Figure 1, Grip strength dynamometer (Lode dynamometer, Lode BV, Groningen, The Netherlands) in an adjustable spring suspension

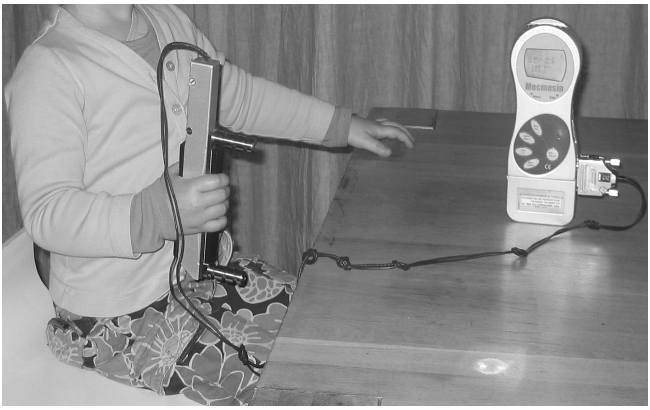

Figure 2, A 4-year-old child holds a Grip strength dynamometer (Lode dynamometer, Lode BV, Groningen, The Netherlands).

In the second protocol, the Visual Feedback protocol, a computer interface that provided visual feedback was added to the American Society of Hand Therapists protocol. On screen, grip force was plotted against time. The Y-axis was scaled from no force at the bottom of the plot to maximum force at the top of the plot. This scale was manually adjusted in the software before each measurement based on the estimated strength of the specific child. When needed, the scale was adjusted after the first trial. This way, every child could almost reach the top of the plot.

In the third protocol, the Suspension protocol, the grip strength dynamometer (Lode BV) was used with a spring suspension so that the child did not have to support the weight of the dynamometer (0.6 kg, Figure 2). The spring suspension was placed at an appropriate height so that hand and arm positions conformed to those specified in the American Society of Hand Therapists protocol.

For all tests the dynamometer was linked to a computer for data gathering and was reset before each measurement. The grip strength of both hands was measured, and the handlebars were in position 2 during testing.(15) A mean of 3 maximum voluntary contractions (MVC's) was recorded for each hand. The time between each MVC trial was approximately 30 seconds and time between measurements of the different protocols was about 5 minutes. All children were seated in an appropriately adjusted chair during the measurements.

All testing was performed during the morning hours in a quiet environment. The testing was performed by 2 researchers (HMM & MDK). One researcher (HMM) performed all the tests; the second researcher assisted with setup and registration.

Starting hand-side was randomized. Because the ASHT protocol was already measured previously, we only randomized the Visual Feedback protocol and Suspension protocol in our second research population. Before the start of each measurement, the subject was told, "Squeeze as hard as you can!" A retest was performed under the same conditions. Due to logistic reasons at the school where the measurements were obtained, the average retest interval time was relatively long (mean 27 days, range: 3-46).

Statistical methods

For all statistical analyses SPSS v.15 (SPSS Inc., Chicago, IL, USA) was used. The test-retest reliability of measurements was determined with the intraclass correlation coefficient (ICC), the smallest detectable difference (SDD), and the normalized smallest detectable difference. Reliability was visualized by means of Bland-Altman plots.(16)

The intraclass correlation coefficient (ICC) is the ratio of variance of interest (inter-subject variance) over the combined variance of interest and error variance (inter-subject plus intra-subject variance).(17)

The SDD, which is the amount of change between tests that is needed to detect a real difference in a subject's performance, is sometimes referred to as smallest real difference(18) or minimal detectable change.(19) For a 95% confidence level, the SDD is calculated as $1.96 \times \sqrt{2} \times$ SEM (standard error of the measurement) where the SEM is the square root of the error variance. (20, 21) The magnitude of the intraclass correlation coefficient indicates the ability to discriminate among subjects, and the SDD is used to calculate error in the original unit of measurement.(17, 20, 22-24) When 2 measurements differ more than the SDD, the change represents a real (non error) change in strength.(20)

The normalized SDD is the above-mentioned SDD expressed as a percentage of the mean maximum voluntary contractions. The normalized SDD can easily be interpreted from a clinical point of view. For example, a SDD of 25% indicates that the follow-up should differ by at least 25% from base-line measurement to indicate a real (non error) change in grip strength.

To test for statistically significant differences among the reliability of the 3 protocols, we used the methods described by Schreuders and colleagues (6) and Stratford and Goldsmith.(25) In short, the reliability of the ASHT protocol was compared to the other two protocols using a variance ratio test. The Visual Feedback protocol and the Suspension protocol were compared as paired samples by calculating the difference between test and retest for each of the assessment methods. Given that the variance of a difference score is equal to the variance of a single measure times two, the statistical test provides information about the extent to which the error variances, and ultimately the SEMs of the different protocols, differ.(25)

To determine whether subjects produced statistically significantly different force levels in the different protocols, a repeated measures ANOVA was used for the dominant and non dominant hand. If a significant overall effect was found, a post-hoc test using a Bonferroni correction was used to compare between all pairs of protocols. These tests were performed on the data of the separate 3 age groups and also on the complete group.

Results

The Visual Feedback protocol had an intraclass correlation coefficient of 0.97 for the dominant hand and 0.96 for the nondominant hand. The Suspension protocol had intraclass correlation coefficients of 0.96 for both the dominant hand and the nondominant hand. These data are similar to previously reported intraclass correlation coefficients of 0.96 for the dominant hand and 0.95 for the nondominant hand in children.(9) Intraclass correlations for different age groups and protocols are shown in Table 1. For all 3 protocols, the normalized SDD ranged from 19% to 27% for the total population.

When we compared the reliability of each protocol for the dominant hand and the nondominant hand in children, we found no statistically significant differences for most protocols (Table 2). There was, however, a small but statistically significant difference between the reliability of the American Society of Hand Therapists protocol and the Suspension protocol for the nondominant hand for the nondominant hand (Table 1).

*Table 1, Results regarding reliability of GRIP1 population on the ASHT-protocol and of reliability of GRIP2 population on the Visual feedback and Suspension protocols in children with no upper limb impairment**

GRIP1 (n = 104)		Age group (y)	n	Mean	SDD	SDD (%)	ICC	95% CI
	Dominant hand	**(4-6)**	30	66.9	18.4	27.6	0.91	0.83-0.96
	Nondominant hand	**(4-6)**	30	63.2	22	34.9	0.84	0.68-0.92
	Dominant hand	**(7-9)**	39	118.7	33.9	28.5	0.78	0.62-0.88
ASHT protocol	**Nondominant hand**	**(7-9)**	39	110.8	28.4	25.6	0.79	0.64-0.88
	Dominant hand	**(10-12)**	35	184.6	31.2	16.9	0.92	0.84-0.96
	Nondominant hand	**(10-12)**	35	174.7	40.5	23.2	0.82	0.68-0.91
	Dominant hand	**(Total group)**	104	125.9	29.2	23.2	0.96	0.95-0.98
	Nondominant hand	**(Total group)**	104	118.6	32	27.0	0.95	0.93-0.97
GRIP2 (n = 63)								
	Dominant hand	**(4-6)**	16	61.9	16.4	26.5	0.93	0.81-0.97
	Nondominant hand	**(4-6)**	16	57	17.1	29.9	0.92	0.52-0.96
	Dominant hand	**(7-9)**	22	116.6	23.7	20.3	0.90	0.79-0.96
Visual Feedback protocol	**Nondominant hand**	**(7-9)**	22	106.5	25.7	24.2	0.85	0.68-0.94
	Dominant hand	**(10-12)**	25	165.5	28.6	17.3	0.93	0.86-0.97
	Nondominant hand	**(10-12)**	25	154.5	34.2	22.2	0.87	0.72-0.94
	Dominant hand	**(Total group)**	63	122.1	24.6	20.1	0.97	0.95-0.98
	Nondominant hand	**(Total group)**	63	113	27.7	24.5	0.96	0.93-0.97
GRIP2 (n = 63)								
	Dominant hand	**(4-6)**	16	70.8	16.6	23.5	0.92	0.79-0.97
	Nondominant hand	**(4-6)**	16	71.4	18	25.2	0.93	0.77-0.97
	Dominant hand	**(7-9)**	22	124.3	29.4	23.7	0.86	0.70-0.94
Suspension protocol	**Nondominant hand**	**(7-9)**	22	116.3	25.4	21.8	0.87	0.72-0.94
	Dominant hand	**(10-12)**	25	173.9	37.2	21.4	0.88	0.75-0.95
	Nondominant hand	**(10-12)**	25	162.5	25.6	15.8	0.90	0.79-0.96
	Dominant hand	**(Total group)**	63	130.4	30	23.0	0.96	0.92-0.97
	Nondominant hand	**(Total group)**	63	123.3	23.5	19.1	0.96	0.93-0.98

**The following indices are shown: Mean of maximal voluntary contractions (in Newtons) for the Jamar-like dynamometer, smallest detectable differences absolute (SDD) and as a percentage (SDD (%)) of the mean strength and intraclass correlation coefficients (with 95% confidence intervals) for every age group.*

Table 2, Comparison of reliability of the different measurement protocols tested

	ASHT Smallest Detectable Difference **(N)**	Suspension Smallest Detectable Difference**(N)**	**p Value**
Dominant hand	29.2	30.0	0.6074
Nondominant hand	32.0	23.5	0.0048
	Suspension Smallest Detectable Difference**(N)**	**Visual Feedback** Smallest Detectable Difference**(N)**	
Dominant hand	30.0	24.6	0.0723
Nondominant hand	23.5	27.7	0.1078
	ASHT Smallest Detectable Difference**(N)**	**Visual Feedback** Smallest Detectable Difference**(N)**	
Dominant hand	29.2	24.6	0.116
Nondominant hand	32.0	27.7	0.207

Bland-Altman plots of the mean versus the difference of the maximum voluntary contractions (MVC) of the test and retest show that the data were evenly distributed around the zero-difference line. The plots illustrate similar differences between tests and retests for weaker (mostly younger) and stronger (mostly older) children when expressed in absolute strength (in Newton) for all protocols (Figure 3).(16) However, when the error was expressed as a percentage of the mean maximum voluntary contractions, the measurement error was higher in weaker children than in stronger children. The same effect was seen in the SDD (Table 1). When expressed in original units, SDDs increased with increasing age of the subjects. However, when expressed as a percentage of the maximum voluntary contractions, the SDDs decreased, indicating a greater reliability with increasing subject age.

When we compared the strength in all protocols, we found an overall protocol effect for both the dominant hand ($p < 0.0001$) and the non-dominant hand ($p < 0.0001$). The post hoc tests indicated significantly higher force levels in the Suspension protocol than in the American Society of Hand Therapists protocol and the Visual Feedback protocol (see Table 3). This difference was found in all age groups except when comparing Visual Feedback and Suspension protocol for the nondominant hand of the subjects in the oldest age group. For the total group, the strength during the Suspension protocol was approximately 10% higher than during the American Society of Hand Therapists protocol. Consecutively, the strength during the Suspension protocol was approximately 5% higher than during the Visual Feedback protocol.

Figure 3, Bland-Altman plots of the mean maximum voluntary contractions of the dominant hand measured with a grip strength dynamometer (Lode dynamometer, Lode BV, Groningen, The Netherlands) versus the difference between the mean maximum voluntary contractions (MVC) for the Suspension protocol (above) and the Visual Feedback protocol (below). On the left, absolute differences are plotted; on the right, differences are normalized to grip strength. The dotted lines represent the mean and the limits of the confidence interval.

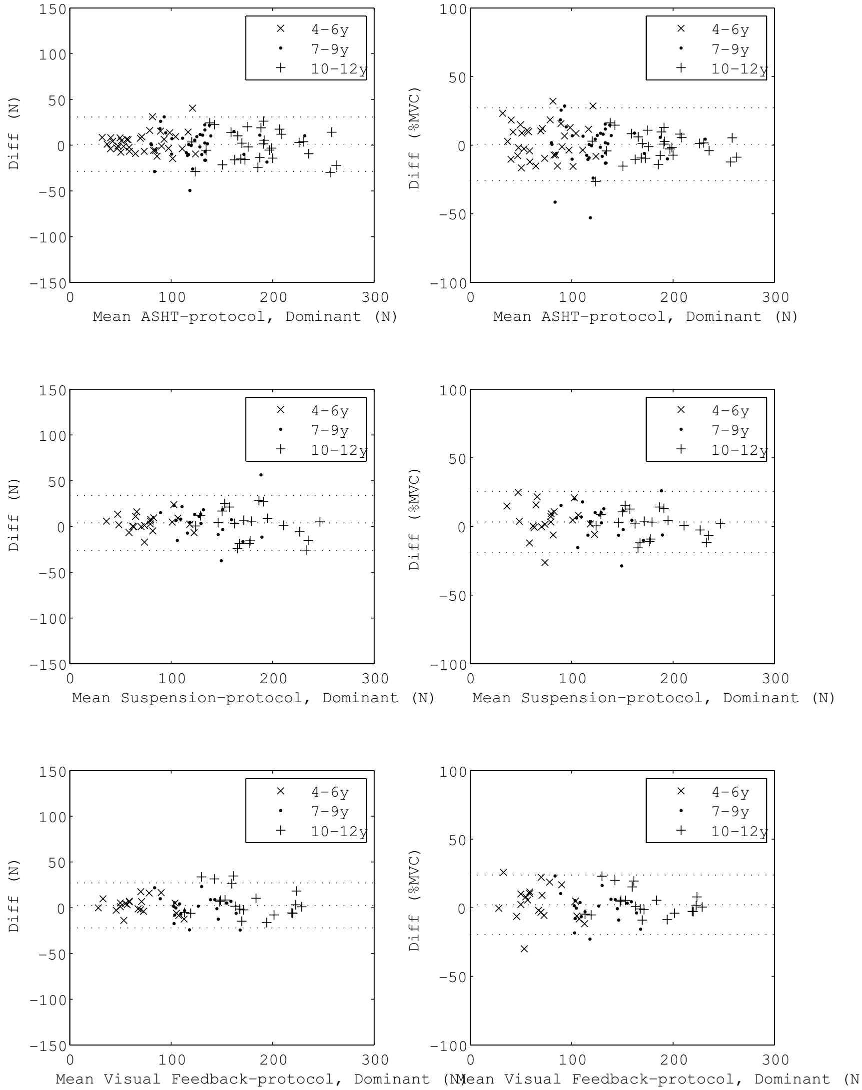

Table 3, Force levels during the three different protocols collected from 128 children (GRIP1 study) Indicated are the results from the post-hoc test of the repeated measures ANOVA with Bonferroni, performed after significant overall condition effects were found (see text).*

Dominant hand	Age (y)	ASHT Protocol (N)	Suspension Protocol (N)	p Value
	4-6	68.4	82.3	< 0.001
	7-9	113.2	126.3	< 0.001
	10-12	172.2	183.7	< 0.001
	All subjects	127.7	140.3	< 0.001
		Suspension Protocol (N)	**Visual Feedback Protocol (N)**	
	4-6	82.3	63.9	< 0.001
	7-9	126.3	116.1	< 0.001
	10-12	183.7	175.5	0.002
	All subjects	140.3	129.0	< 0.001
		ASHT Protocol (N)	**Visual Feedback Protocol (N)**	
	4-6	68.4	63.9	0.025
	7-9	113.2	116.1	0.339
	10-12	172.2	175.5	0.241
	All subjects	127.7	129.0	0.762
Nondominant hand	**Age group (y)**	**ASHT Protocol (N)**	**Suspension Protocol**	**p Value**
	4-6	63.6	79.5	< 0.001
	7-9	105.0	119.7	< 0.001
	10-12	162.0	170.9	0.001
	All subjects	119.4	131.9	< 0.001
		Suspension Protocol	**Visual Feedback Protocol (N)**	
	4-6	79.5	65.8	< 0.001
	7-9	119.7	111.5	0.019
	10-12	170.9	169.4	1.000
	All subjects	131.9	125.3	< 0.001
		ASHT Protocol (N)	**Visual Feedback Protocol (N)**	
	4-6	63.6	65.8	0.419
	7-9	105.0	111.5	0.016
	10-12	162.0	169.4	0.001
	All subjects	119.4	125.3	< 0.001

**The maximum voluntary contraction, expressed in Newtons (N), specific for the age of the subjects is shown under each protocol. Each row represents a comparison for each specific age group. The last column displays the p value of statistical significance.*

Discussion

The first aim of this study was to compare the reliability of 3 different measurement protocols in children using a grip strength dynamometer. The second aim was to study the effect of these protocols on maximum strength. The grip strength dynamometer was found to be reliable in these children: the intraclass correlation coefficient was 0.95 or higher, and the normalized SDD showed values ranging between 19% and 27% regardless of the measurement method. We found no clear effect of age on the intraclass correlation coefficients, although the intraclass correlation coefficients of the middle age group (age range, 7-9 years) had lower values when the American Society of Hand Therapists protocol was used.(9)

The reliability of the measurements in children was comparable to reported values in adults.(2-6, 23, 26) Because intraclass correlation coefficients are determined not only by measurement error but also by inter-subject variations intraclass correlation coefficient values in different studies are difficult to compare. This effect of inter-subject variations on intraclass correlation coefficient values may also explain why all three age groups had intraclass correlation coefficients lower than the intraclass correlation coefficient of the total group. A better comparison of reliability can be made with the (normalized) SDD. For each protocol, the normalized SDDs ranged between 19% and 27%. Comparing the reliability of the different protocols, we found no significant differences (Table 2).

The normalized SDD decreased with the increasing age of the subjects. The SDDs of around 20% in the oldest age group (Table 1) are comparable to values found in literature on adults.(6, 7, 23, 24) In our study, the absolute SDDs were somewhat higher for the older children compared to the younger children, but as the younger children showed less grip strength the normalized SDD of the younger children were higher. It is difficult to determine whether proper understanding the task had any influence on the reliability. However, in our experience and somewhat to our surprise, all children, including the 4-year olds, seemed to easily understand the instructions.

We expected to find that the Visual Feedback and Suspension protocols, when compared with the American Society of Hand Therapists protocol, would generate better reliability and higher grip strength measurements. As described earlier, the Suspension protocol was designed to focus the subject's effort on increasing grip strength instead of keeping the apparatus at the correct level. Similarly, we anticipated that Visual Feedback of task performance would provide more consistent values between the test and retest and would motivate the subject to exert higher force, as reported previously in adults.(11-13) Although we did not find an effect in these healthy children, this may be different when measuring patients with specific disabilities. For example, attention deficit disorder patients may specifically benefit from the Visual Feedback protocol and patients suffering from neuro muscular disorders with a decreased strength could benefit from the Suspension protocol since the device may be too heavy for them.

The second aim of this study was to determine the maximum force produced in the 3 protocols. We found that strength during the Suspension protocol was significantly higher ($p < 0.05$) than during the other 2 protocols, with the exception of the nondominant hand of subjects aged 10 to 12 years when compared to the Visual feedback protocol. The latter difference seemed to be coincidental because it only occurred in the non-dominant hand in only this particular age group (Table 3). In addition, for the oldest age group and the total group, a statistically significant difference was found between the American Society of Hand Therapists protocol and the Visual Feedback protocol in the nondominant hand (Table 3). The finding of the highest force levels in the Suspension protocol may be explained by subjects being able to focus solely on strength output instead of keeping the relatively heavy dynamometer on an equal level. Although the differences in strength were relatively small (maximum difference ± 10%), these differences are important for comparing data from different protocols. It should be noted that a slightly higher maximum voluntary contraction could improve reliability when expressed in terms of the normalized SDD, because with an increased maximum voluntary contraction, the effect of measurement error would be less.

There are some limitations to our study. First, because this study was performed only in children without impairment of an upper limb, no conclusion can be drawn regarding reliability in children with such impairments. Furthermore, in some cases the interval between the test and the retest was relatively long (range, 3-46 days; average, 27 days). Even though this relatively long interval was not planned, it was the result of logistics related to the primary school. However, no overall increase in strength was found in the retest measurement, a finding illustrated by the evenly distributed data for all age groups around the zero-difference line in the Bland-Altman plots in Figure 3. This suggests that the interval between measurements was not long enough to allow a systematic improvement in strength in the retest measurements. In this study, we used a grip strength dynamometer with the handlebar in position 2 in all children. We found that with this device, even the youngest children were able to perform a maximum voluntary contraction, despite a more distal placement of the fingers on the handle bar. We preferred to use the handlebar in the same position. Although data are difficult to compare due to different hand sizes, we argue that changing handle size between subjects does not improve the comparability among subjects or the comparability when following subjects over time.

Although our study shows the effect of age on the reliability of grip strength measurement, it remains more or less arbitrary to conclude on a minimal age for performing reliable grip strength measurements. Because normalized SDD values may be a more clinically relevant outcome measure than intraclass correlation coefficients or absolute SDDs, we have compared our normalized SDD values with those in the literature on adult grip strength reliability. The oldest age group (age range, 10-12 years) described in a previous study(9) had intraclass correlation coefficient values and SDD values equal to those found in adults.(6, 7, 23, 27) This indicates that all 3 protocols in our study are at least as reliable when used in children aged 10 to 12 years. The normalized SDD decreased slowly with the increasing age of the subjects, indicating higher reliability with age. However, we suggest that even in the youngest children, the reliability of any of those 3 protocols may be sufficient for follow-up evaluations.

We did not find any real arguments to prefer using visual feedback or suspending the grip strength dynamometer over the American Society of Hand Therapists protocol in this group of children without known pathologies. How applicable our findings are to children with some kind of disability is unknown. When using visual feedback, we did find that the healthy children enjoyed the testing more than without feedback. Although we did not objectively measure that level of satisfaction, it may have enabled a longer attention span (while maximum voluntary contractions were produced) than when the American Society of Hand Therapists protocol or the Suspension protocol was used. Overall, each protocol for using the grip strength dynamometer was equally reliable to use in children from 4 years and older. When the weight of the instrument was relieved in the Suspension protocol, the force was significantly higher (10%). However, because there were no statistically significant differences in reliability among the 3 protocols, practical factors may dictate the most appropriate protocol to be used. From a practical point of view, the American Society of Hand Therapists protocol is the most simple of the 3 to perform and requires no extras like spring suspension or a computer interface.

Chapter 3

Visual feedback and weight reduction of a grip strength dynamometer do not increase reliability in healthy children

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Chapter 4

Growth Diagrams for Grip Strength in Children

Abstract

Grip strength dynamometers are often used to assess hand function in children. The use of normative grip strength data at follow-up is difficult because of the influence of growth and neuromuscular maturation. As an alternative, infant welfare centers throughout the world use growth diagrams to visualize normative growth. The aim of this study was to develop similar growth diagrams for grip strength in children. Grip strength, hand-dominance, gender, height, and weight of 225 children, 4 to 12 years old, were measured. We developed separate statistical models for both hands of boys and girls for drawing growth curves. Grip strength increased with age for both hands. Overall, grip strength increased with age for both hands. For the whole group the dominant hand produced higher grip strength than the nondominant hand ($p < 0.001$) and boys were 2%-34% stronger than girls ($p < 0.001$) across the different age groupsBecause grip strength measurements are accompanied by a rather large variance, the growth diagrams (presenting a continuum in grip strength) make it possible to better visualize grip strength development over time corresponding to a more exact age. Depending on the accuracy needed, the use of one single combined diagram could be considered.

Introduction

Grip strength measurements are often used to assess hand function in, for example, patients with trauma or congenital problems or in case of degenerative diseases (1). Hand dynamometers frequently used to measure grip strength are the Jamar dynamometer (Jamar; TEC, Clifton, NJ) or equivalent devices such as the lode dynamometer (Lode BV, Groningen, The Netherlands).

Normative and reliability data on these dynamometers have been published for both adults and children (2-11). For adults, a reference table with normative data is generally used. For children, normative data are also often presented in a table format, in which mean grip strength data are given for 1-year or 2-year intervals with its standard deviation (9, 12). Alternatively, studies have presented equations relating grip strength data with variables such as age, gender, height, weight, or body mass index (10).

Using the normative data as reference values can be rather cumbersome when measuring a child at follow-up as a result of the increase in strength when a child grows. A child does not only increase in length, but also for example in weight, bone mass and muscle volume. This growth in children complicates the interpretation of changes in strength measured after interventions such as surgery or rehabilitation, because outcome is influenced both by growth and the intervention. To discriminate among contributions of growth, intervention effects, or disease progression, a more easily interpretive model than a table with 1-year or 2-year intervals would be valuable.

As an alternative to the mentioned presentation of normative data, in children, an intuitive diagram in which strength is plotted against age would give an immediate indication of the strength that can be expected at the child's age using a continuous age scale. In addition variation in strength can also be accounted for using the correct percentiles. Such growth diagrams for length and weight have been developed for use at infant welfare centers across the world (13-16). Use of these diagrams for grip strength would give a quick and easy insight into grip strength development during growth. For example, it could be very valuable when treating children with congenital hand malformations or children with neuromuscular disorders who receive longstanding treatment to follow the child's progress.

Our first aim was to create growth diagrams for grip strength making normative data of grip strength more intuitive and easily accessible from a clinical point of view. To do so, we first determined which variables in addition to age such as hand dominance, gender height and weight influenced grip strength in our population. Then, we used these variables to develop a model for drawing grip strength growth curves in an easily interpretable diagram for clinical use. The second aim of our study was to see if an accurate model for grip strength could still be developed using only simplified average analysis combining both genders and dominant hand and nondominant hands into a single diagram.

Materials and Methods

After approval of the Institutional Review Board and after informed consent of the parents, we approached children from a local primary school without upper limb impairment for participation. Hand dominance and upper extremity problems that could influence hand strength were determined by evaluating parents' responses to a questionnaire. Children with a history of upper extremity trauma or abnormalities were excluded. For this study, we measured an extra 121 children in addition to the 104 children used in our previous study on the reliability of the grip strength dynamometer in children (11). A total of 225 children, aged 4 to 12 years, were included in this study. Of all the children studied, 94% were right-handed (Table 1).

Table 1, Number of participants divided among gender and age

Age (years)	Boys (number)	Girls (number)	Total
4	12	11	23
5	13	13	26
6	11	12	23
7	13	14	27
8	12	15	27
9	12	14	26
10	13	12	25
11	12	12	24
12	12	12	24
Total	110	115	225

We used a Jamar-like dynamometer (Lode dynamometer; Lode BV, Groningen, The Netherlands) for all measurements (Fig 1). The Lode dynamometer is an electronic dynamometer similar to the Jamar dynamometer. It operates similar and is calibrated to measure the same outcome as the Jamar dynamometer. In a previous study we quantified the measurement error of this instrument in children and found the Lode dynamometer to be reliable in healthy children from 4-12 years old. Reliability increased with age and children of 12 years old had similar reliability as adults (11). The dynamometer was used as recommended by the American Society of Hand Therapists. The subject sits with the shoulder adducted, elbow flexed in a 90 degree angle, and the wrist in a neutral position (17). The Lode dynamometer, with the handlebar in Position 2, was used to measure grip strength of both hands (18). After each measurement, we reset the dynamometer. All measurements were performed in a randomized order by the same researcher (HMM). The children were seated in an appropriately adjusted chair during measurements. Before the start of each measurement, the subject was told, "Squeeze as hard as you can!" A mean of three maximum voluntary contractions was recorded for each hand. In case one of the measurements showed a difference of more than 10% with the other measurements, we cancelled that measurements and added a fourth measurement. The mean of the three remaining values was calculated.

Figure 1, A 6 year old child holds a Jamar-like dynamometer (Manufacturer: Lode B.V., Netherlands)

To develop the growth curves, we first estimated the centiles for grip strength using Altman's method of absolute scaled residuals (19). Because a visual inspection did not reveal skewness or nonnormal kurtosis, we decided not to transform the dependent variable. In a first model, grip strength was modeled as a function of the age. To allow for nonlinearity in the mean, we used restricted cubic splines with three knots placed at the 10th, 50th, and 90th centiles. The standard deviation was estimated using the regression function of the absolute residuals. We estimated separate relationships for boys and girls for both the dominant and nondominant hands.

The mentioned model was compared with a more complex model that also included weight and length next to age. All factors were included in this more complex model as a restricted cubic spline with three knots. Residuals of the various models were checked for normality and serial correlation.

We used a partial F test to calculate differences in grip strength by gender and hand dominance. Although we found major differences between boys and girls and between both hands, we also made a combined diagram for all boys, girls, and both hands combined. Although this combined graph is less accurate in predicting normative data for an individual subject, we present it for use as a first estimate in clinical situations in which four separate graphs may be too cumbersome. All estimations and calculations were done using SAS 9.1 (SAS Institute, Inc, Cary, NC).

Results

Grip strength increased with age in both hands. In the whole group, the dominant hand produced higher ($p < 0.001$) grip strength than the nondominant hand and boys were significantly stronger ($p < 0.001$) than girls. (Tables 2 and 3)

The differences between boys and girls were not the same for each age. For the youngest group of 4-6 years, the boys were 24%-34% stronger. In the middle age group of 7-9 years old, the boys were 2%-9% stronger and for the oldest age group (10-12 years), the boys were 3%-11% stronger. For both genders, differences in grip strength between dominant and nondominant hands ranged from 2 to 17 Newtons.

Table 2, Grip strength in Newtons for boys is shown as the mean of the MVC, standard deviation, minimum MVC, and maximum MVC

MVC = maximum voluntary contraction; D = dominant; ND = nondominant.

Boys	Age (years)	Number	Mean	Standard deviation	Minimum	Maximum
D	4	12	65.9	12.9	50.2	93.1
ND			61.7	14.2	39.9	85.2
D	5	13	84.0	17.6	53.3	112.8
ND			73.5	14.4	47.3	94.8
D	6	11	97.6	16.3	70.0	115.4
ND			92.2	16.7	64.7	123.9
D	7	13	115.7	22.0	80.2	145.7
ND			106.1	15.6	83.9	135.6
D	8	12	115.8	29.2	69.3	152.9
ND			110.8	27.4	69.8	158.0
D	9	12	139.6	24.0	108.2	179.8
ND			137.1	24.0	102.9	176.7
D	10	13	159.5	36.3	126.9	266.1
ND			151.9	37.4	96.4	245.9
D	11	12	195.4	36.0	139.9	251.7
ND			179.8	32.8	142.9	251.1
D	12	12	219.4	35.0	151.1	288.8
ND			202.8	31.8	147.9	271.2

Table 3, Grip strength in Newtons for girls is shown as the mean of the MVC, standard deviation, minimum MVC, and maximum MVC

MVC = maximum voluntary contraction; D = dominant; ND = nondominant.

Girls	Age (years)	Number	Mean	Standard deviation	Minimum	Maximum
D	4	11	48.6	12.7	36.2	70.8
ND			46.3	11.9	25.3	61.0
D	5	13	64.1	16.9	44.3	97.2
ND			59.3	14.1	31.4	79.1
D	6	12	82.7	19.1	57.9	123.5
ND			70.5	10.2	53.8	87.4
D	7	14	107.4	18.1	86.0	140.6
ND			96.9	15.1	78.7	130.8
D	8	15	116.0	23.0	77.4	148.4
ND			107.1	19.0	73.2	136.2
D	9	14	133.8	29.9	93.7	185.2
ND			126.3	27.7	83.7	176.3
D	10	12	152.2	32.6	83.3	193.0
ND			138.6	33.6	68.1	174.9
D	11	12	190.2	32.5	151.0	249.3
ND			175.0	30.5	137.8	231.7
D	12	12	197.6	42.6	109.2	265.4
ND			181.9	34.8	105.4	223.3

To determine correct models for predicting grip strength in the dominant and nondominant hands of the boys and girls separately, we compared the more complex model including the variables age, height, weight, and gender with the simpler model that included age alone. R2 for the dominant and nondominant hands are only slightly lower in the simpler model with age as the only independent variable of grip strength. (Table 4)

*Table 4, The R2 of the models used to draw the growth curve for boys and girls separately for either the dominant or the nondominant hand. The shaded lines indicate the simpler model where as the non shaded line is the more complex model accounting for height and weight besides age.**

Sex and hand dominance	Model variables	R^2
Boys - Dominant	Age	79%
Boys - Dominant	Age, Height and Weight	80%
Girls - Dominant	Age	80%
Girls - Dominant	Age, Height and Weight	83%
Boys - Nondominant	Age	77%
Boys - Nondominant	Age, Height and Weight	79%
Girls - Nondominant	Age	80%
Girls - Nondominant	Age, Height and Weight	84%
All combined (both hands and both genders)	Age	76%
All combined (both hands and both genders)	Age, Height and Weight	80%

**R2 indicate the explained variance of the simple model, including age, and a more complex model, including age, height, and weight.*

Because we decided the benefits of a simpler model using age only outweighs the slight increase in predictability of grip strength achieved by the more complex model, we present only the simpler model. The simpler statistical models for grip strength as a function of age in the dominant and nondominant hands of boys and girls separately were converted into growth diagrams (Figures 2-5). As well as the curve of the population mean, these diagrams show the centiles that correspond to each standard deviation (SD) added or subtracted from the mean: 2.5%, 16%, 50%, 84%, and 97.5% centiles correspond to -2 SD, -1 SD, mean, +1 SD, and +2 SD.

Finally, we included Figure 6 where the mean hand strength of the dominant and nondominant hands was plotted against age for boys and girls combined. The use of just one diagram of both genders and both hand could be considered more practical in some clinical situations where 4 different diagrams are to inconvenient to use. Because this combined diagram includes all data not selective for gender and hand dominance, the goodness of fit is lower compared to Figures 2-5, although this effect on the goodness of fit is only small (Table 4).

Figure 2, Grip strength in Newton for the dominant hand in boys plotted against age in years. The centiles 2.5%, 16%, 50%, 84% and 97.5% are shown.

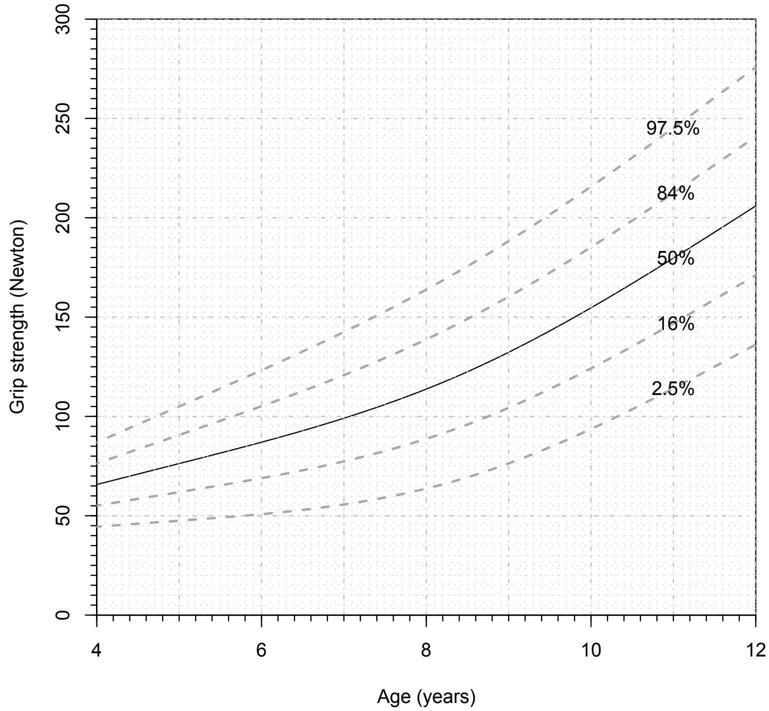


Figure 3, Grip strength in Newton for the nondominant hand in boys plotted against age in years. The centiles 2.5%, 16%, 50%, 84% and 97.5% are shown.

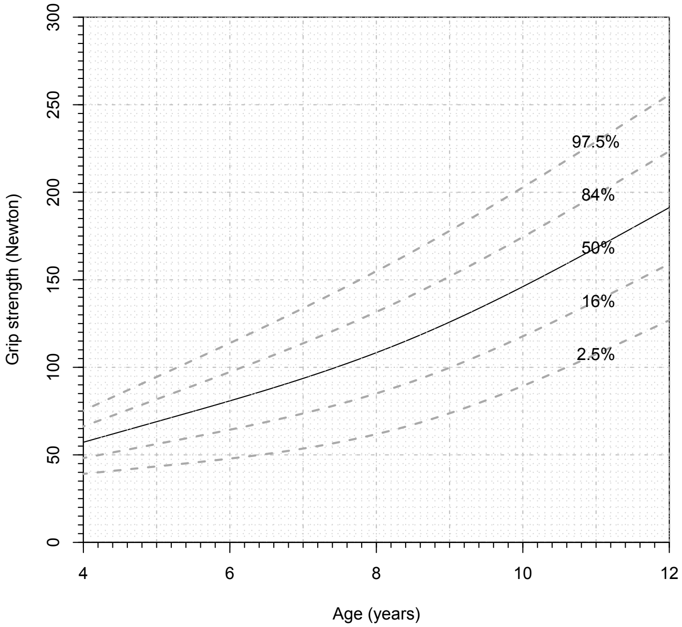


Figure 4, Grip strength in Newton for the dominant hand in girls plotted against age in years. The centiles 2.5%, 16%, 50%, 84% and 97.5% are shown.

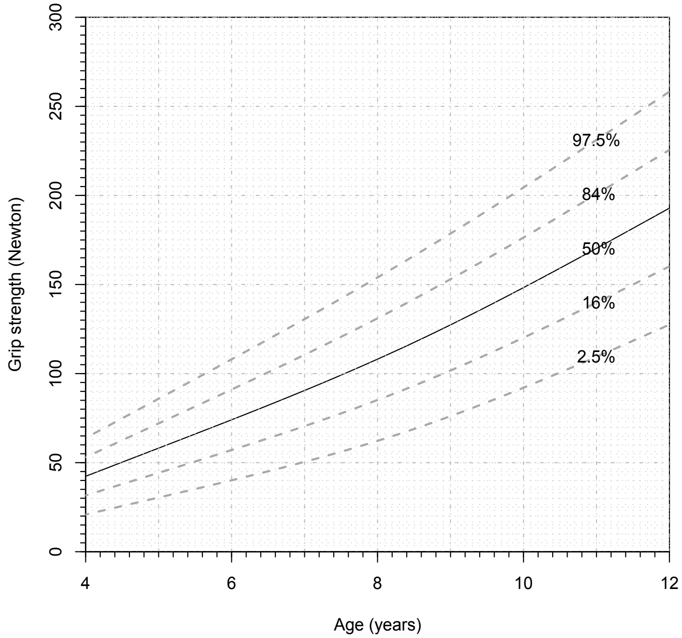


Figure 5, Grip strength in Newton for the nondominant hand in girls plotted against age in years. The centiles 2.5%, 16%, 50%, 84% and 97.5% are shown.

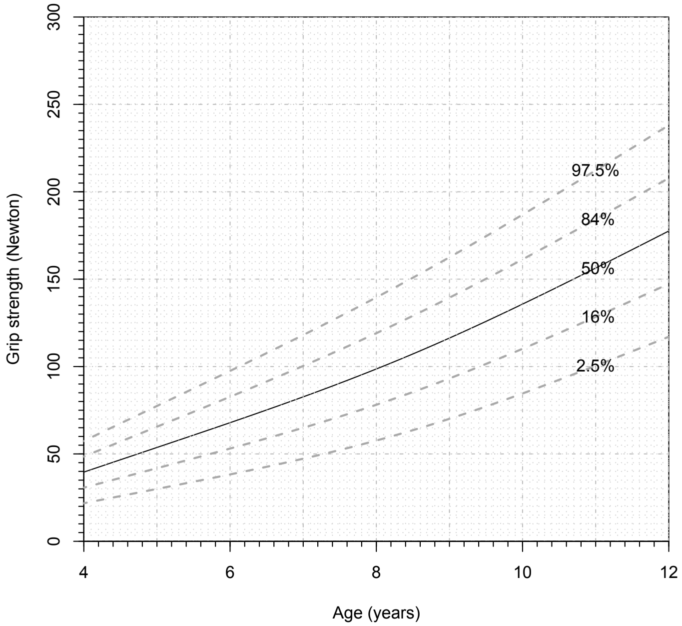
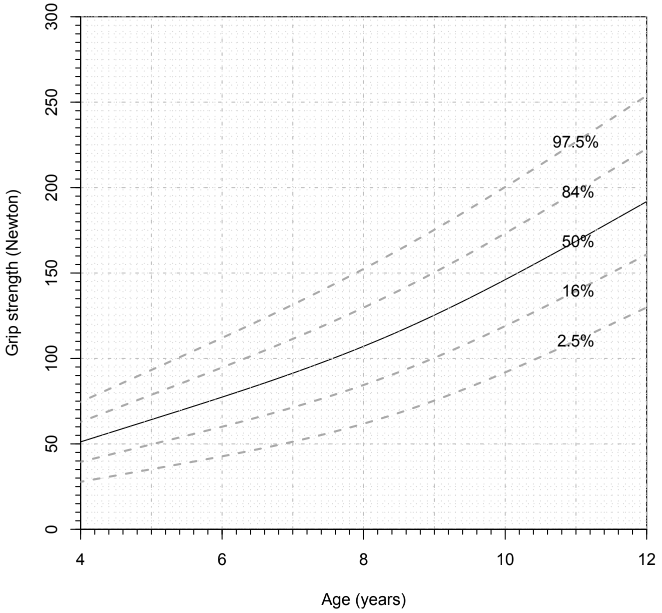


Figure 6, Grip strength in Newton for the mean hand strength (dominant and nondominant combined) for all subject (boys and girls combined) plotted against age in years. The centiles 2.5%, 16%, 50%, 84% and 97.5% are shown.



Discussion

Our general aim in this study was to develop a simple and intuitive method of presenting normative grip strength data in children. Normative data are usually reported in table format, presenting grip strength by age group, gender, and hand dominance. However, when this method is used to compare grip strength values in children over time, it becomes difficult to verify grip strength changes over time against the reference data. The wide ranges in grip strength per age do not give a clear overview of a child's grip strength development over time.

As an alternative to the classic method of reference tables, we developed an intuitive diagram showing grip strength development over time, the intention being to allow for easier and insightful registration of a child's grip strength development in the same way as growth diagrams are developed for increase in height over time. The growth diagrams for grip strength shown in Figures 2 through 5 were developed as tools to be used in a clinical setting. By allowing a child's grip strength to be plotted over time, they show how his or her grip strength has developed relative to the reference data contained in the diagram. If a child's strength is plotted at a certain distance from a centile line, a change in this distance at follow-up may indicate an increase or decrease in strength relative to his or her age. An additional advantage for individual patient measurements is the continuous nature of the diagrams. A table containing reference data is difficult to use as such values are given per year or 2-year interval. In contrast, the growth diagrams present a continuum in grip strength values allowing measurement outcome to be compared with a more exact age of any child.

In addition we also present a model for both hands and with both boys and girls combined. This model is presented in Figure 6. By sacrificing some "goodness of fit" (Table 4) the use of just one single diagram could be more practical in clinical settings. One important thing to consider using the models presented in figures 2-6 is that the centile lines are based on the standard deviation of these measurements. As a result 5% of all healthy children will automatically fall outside the outer centile lines.

The grip strength data in our study were somewhat lower than the reported normative data on grip strength that have been measured using a handheld dynamometer. To prevent inadvertent dropping, Mathiowetz et al supported the instrument around the readout dial and they scored a higher grip strength of 30% or more (9). In another study, van den Beld et al used a height-adjustable table on which to rest the instrument. Their results in grip strength were approximately 19% higher (10). Finally, de Smet et al used no suspension method and measured grip strengths that were approximately 5% higher (12). The lower grip strength in the present study may partly be explained by the fact that we used no form of suspension and that the children therefore needed to lift the weight of the instrument. We recently found that suspension of the dynamometer when measuring grip in similar age-groups can increase the force output by 10%. In this same study the reliability did not increase by adding visual-feedback to the strength measurements. However this study has not yet been published (20).

Some limitations must be mentioned with regard to our study. First, it should be noted that the growth diagrams apply only to a healthy population of children and do not represent the development of the grip strength of a child with hand pathologies such as neuromuscular diseases or congenital malformations. Furthermore, our data only applies to the age range of 4 to 12 years old and no reliable predictions can be made for children older than 12 years. Furthermore, our data only applies to the age range of 4 to 12 years old and no reliable predictions can be made for children older than 12 years. In a previous study, we quantified the measurement error of this instrument in children. The lode dynamometer was found to be reliable in healthy children from 4-12 years old. Reliability increased with age and children of 12 years old followed similar reliability as adults (11). In addition, based on our clinical experience when measuring children it is generally too difficult to reliably measure children as young as 3 years. For these reasons we used the lower age limit of 4 years. We studied the group from 4-12 years old, since this age group is relevant in our work with patients with congenital hand malformations. During the period from 4 to 12 years these children are often treated multiple times for their specific congenital malformations. Intervention and intensive therapy are of great importance to their development, dexterity and growth.

Another limitation of our study is that the diagrams summarize cross-sectional grip strength data and not longitudinal data taken from a group of children measured repeatedly during their development. In addition it should be noted that there is a large variance in measurement outcome when repeated grip strength measurements are performed in reliability studies (6, 8, 10, 21). Our quantification of variance in a recent paper on the reliability of the hand strength dynamometer in children showed a smallest detectable difference of 23% to 27% of the outcome (3, 11). It should be noted that adding more subjects to our study will not change the distance between the centile lines in the model, it would only allow for a more accurate estimation of the mean and centiles lines.

In clinical settings in which it is important to follow the development of a child's grip strength, a growth diagram would give a good indication of individual development relative to normative values. In this way, a possible effect of treatment or therapy may quickly be visible as a gain or loss of grip strength over time. Our grip strength plots (Figures 2 through 5) for each specific target group provide the observer with the best model for comparing measurement outcome. Because these diagrams are more specific, they show a better fit to the data. Depending on the accuracy needed at follow-up, the use of one single diagram might be considered. At the cost of losing some goodness of fit, a single combined diagram would be much simpler and more convenient to use (Fig 6). Either way, because the diagrams give observers a practical tool for tracking multiple grip strength measurements of a growing child over time, they might be suitable for inclusion in a patient dossier.

Chapter 4

Growth Diagrams for Grip Strength in Children

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Reliability hand strength measurements using the Rotterdam Intrinsic Hand Myometer (RIHM) in children - American Journal of Hand Surgery: 2008;33(10):1796-801

Chapter 5

Reliability on hand strength measurements using the Rotterdam Intrinsic Hand Myometer (RIHM) in children

Abstract

Purpose: Grip-strength and pinch-strength measurements are often used to assess hand function. However, both measure a number of muscle groups in combination and especially grip strength is dominated by extrinsic hand muscles. The Rotterdam Intrinsic Hand Myometer (RIHM) was recently introduced to measure the force that individual fingers and thumb can exert in different directions. Aim of this study was to establish reliability of these measurements with the RIHM in children.

Methods: Sixty-three healthy children between 4-12 years old participated in this study. The RIHM was used to measure thumb palmar abduction, thumb opposition, thumb flexion in the metacarpo phalangeal (MCP) joint, index finger abduction and little finger abduction. A retest was performed with an average test-retest interval of 26 days.

Results: For the thumb, palmar abduction strength had intra-class correlation coefficients (ICC) of 0.98 for both hands. For thumb opposition and flexion in MCP, ICC's were 0.97 and 0.98 for the dominant and non-dominant hand. Index finger abduction had ICC's of 0.94 and 0.95 and little finger abduction 0.90 and 0.92. The smallest detectable differences (SDD) for dominant and non dominant hand were for thumb palmar abduction 15% and 15%, for thumb opposition 12% and 9%, for thumb flexion (at MCP level) 12% and 9%, for abduction of the index finger 17% and 17%, and for little finger abduction 26% and 26%.

Conclusion: We found that the RIHM was reliable to use in children. ICC's and SDD's were comparable to those of the RIHM in adults as well as to values found for pinch and grip strength in children. Since the RIHM measures more specific aspects of hand function than grip and pinch, adding the RIHM to measurement protocols may contribute to a more complete overview of a child's hand function.

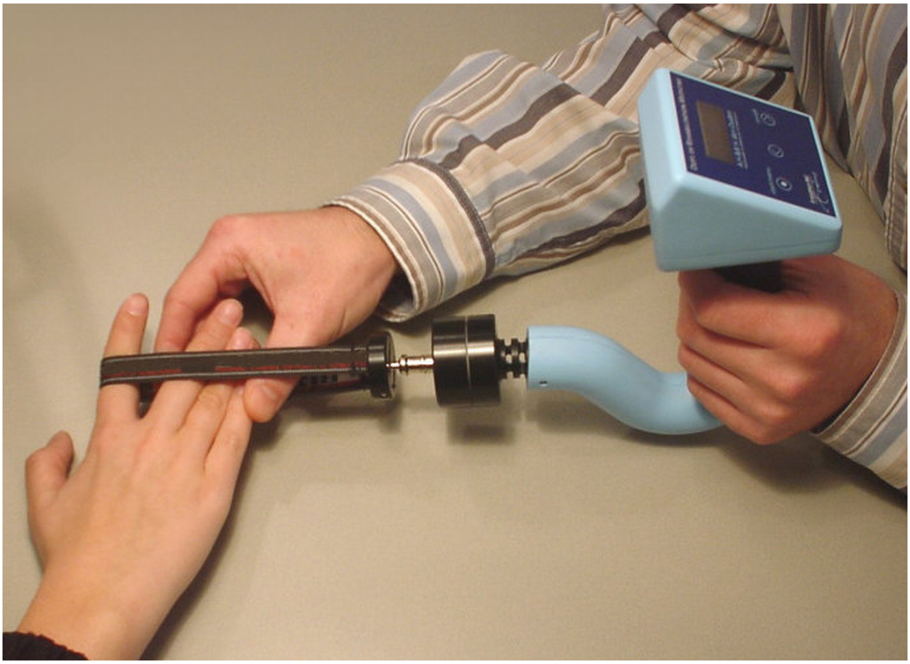
Introduction

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) If hand function is reduced because of trauma or malformations of the hand, a person has to incorporate a whole new coordination pattern for handling objects in life. Instruments regularly used in therapy like the Jamar dynamometer measure predominantly extrinsic muscle strength. The Jamar dynamometer is found to be very reliable in children and adults.(2-9) Strength measurements of the individual fingers of the hand are generally not incorporated in clinical or rehabilitation programs. Because thumb functions like opposition and abduction in combination with the fingers are important functions, measuring these functions more directly than with grip or pinch dynamometers could be very relevant in therapy and rehabilitation.

The Rotterdam Intrinsic Hand Myometer (RIHM) was designed at the Erasmus Medical Center Rotterdam, the Netherlands to measure the strength of the individual fingers and thumb in different directions (Figure 1). This allows measuring more detailed aspects of hand function than with grip-strength and pinch-strength dynamometers and, in some specific situations, allows measuring isolated intrinsic hand muscle strength. For example, when measuring index finger abduction, the resulting force is solely created by the first interosseous muscle. However, other movements are enforced by a combination of multiple muscles. For example, in the case of thumb flexion on MCP level, not only intrinsic hand muscles but also the extrinsic muscle Flexor Pollicis Longus contributes to the movement.

The RIHM has already proven to be reliable in adults, but reliability is unknown for children.(10-11) And because children with congenital hand malformations are often treated soon after birth or very early in live, it would be important to follow their development after intervention. Therefore the aim of our study was to test reliability of the RIHM in children.

Figure 1: Rotterdam Intrinsic Hand Myometer (RIHM) measuring radial abduction of the index finger.



Material & Methods

Population

With approval of the Institutional Review Board and after informed consent of the parents, children of a primary school were approached to participate in this study. All children with upper extremity problems (e.g. trauma, malformations, neurological damage) were excluded from the study. A total of 63 children participated in this study, with age ranging from 4 to 12 years. (Table 1.)

Table 1: Number of participants divided among age groups and gender.

Age (years)	**Boys**	**Girls**	**Total**
4-6	8	8	**16**
7-9	11	11	**22**
10-12	13	12	**25**
Total	**32**	**31**	**63**

Material

The Rotterdam Intrinsic Hand Myometer (RIHM; Figure 1) is a dynamometer that measures strength by means of muscle resistance in a break-test. This so-called break-test is performed while pulling with the RIMH under an angle that is easily controllable.(12) The examiner and subject are seated opposite to each other at a table and the subject is shown and instructed how to keep their finger or thumb in place. Slowly, while this subject is instructed to hold its position, force is increased and after about one second the examiner pulls to “break” the position. This way, different muscles in the hand can be measured.

Measurements

For this study we measured abduction of the index and little finger. In addition, for the thumb, we measured thumb palmar abduction (primarily an action of the Abductor Pollicis Brevis muscle), thumb opposition (primarily the Opponens Pollicis muscle) and thumb flexion in the metcarpo phalangeal (MCP) joint (primarily caused by the intrinsic Flexor Pollicis Brevis muscle). The measurements were repeated 3 times and the mean of the 3 tests was registered. For reliability a retest was performed with an average test-retest interval of 26 days (SD: 11.5).

Statistical Methods:

Test-retest reliability of measurements was analyzed using intraclass correlation coefficient (ICC), smallest detectable difference (SDD) and normalized SDD. Reliability was visualized using Bland-Altman plots.(13)

Intraclass correlation coefficient (ICC) is the ratio of variance of interest (between-subject variance) over variance of interest and error variance (between-subject plus within-subject variance).

The smallest detectable difference is the amount of change between tests that is needed to detect a real difference in a subject’s performance and is sometimes also referred to as the smallest real difference(14) or the or minimal detectable change.(15) For a 95% confidence level, the SDD is calculated as $1.96 \times \sqrt{2} \times SEM$, where the standard error of measurement (SEM) is the square root of the error variance. When two measurements differ more than the SDD, it can be concluded that the change represents a real (non-error) change in strength.(16)

Normalized SDD is the above-mentioned SDD expressed as a percentage of the mean maximum voluntary contraction (MVC). With normalization the SDD's are directly comparable among instruments because they are expressed as a percentage of the mean outcome. In addition, the normalized SDD had the advantage of being easily interpretable from a clinical point of view. For example, a normalized SDD of 25% indicates that the follow-up should differ with at least 25% in order to detect a real (non-error) change in grip strength.

Results

For all muscle strength tests we found high ICC's ranging from 0.90-0.98 for the total group (4-12 years old). More specifically, the index finger had ICC's of 0.94 and 0.95 and the little finger had ICC's of 0.90 and 0.92 for the dominant and non dominant hand, respectively. For the thumb, all measurements ranged between 0.97-0.98 for dominant and non dominant hand. The different age sub-groups showed ICC's of 0.93 and higher for thumb measurements. The index finger scored ICC's of 0.80 and higher, whereas the little finger had the lowest ICC of 0.61. All ICC values are shown in Table 2.

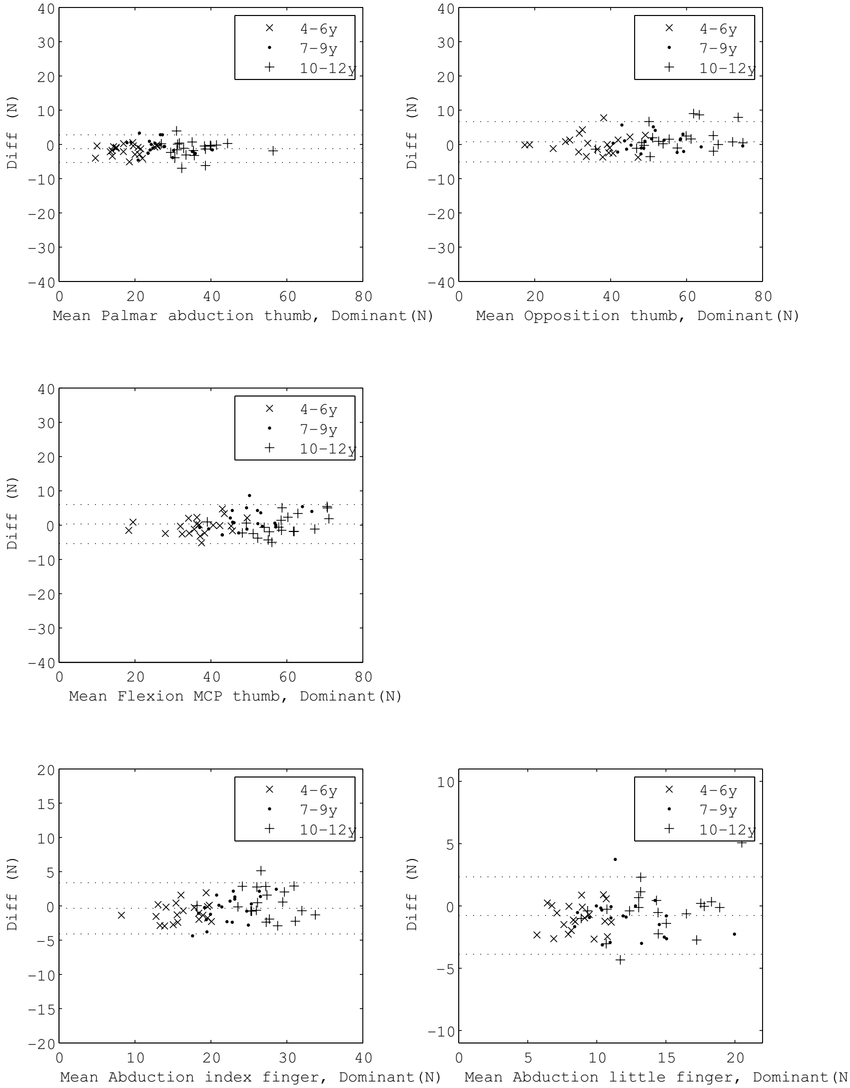
In the Bland Altman plots it is clearly visible that all data are evenly distributed around the zero line (Figure 2). The differences between test and retest were approximately the same for each age group and muscle strength test. The measurement error was higher in the younger and weaker group compared to the stronger and older children when this error was expressed as a percentage of the MVC.

The influence of age on mean MVC, SDD and normalized SDD for all measurements is shown in Table 2. Even though the SDD increased overall with age, the normalized SDD is reduced. This effect is caused by the higher MVC of older and therefore stronger children. The normalized SDD for palmar abduction was 15% and 15% for the dominant and non-dominant hand. MCP flexion had 12% and 9% for the dominant and non-dominant hand. Opposition scored approximately the same with 12% and 9%. Normalized SDD's of the abduction of the index finger were 17% and 17% for dominant and non dominant hands. Finally, the reliability of the abduction strength of the little finger was slightly less with 27% and 26% for dominant and non dominant hand.

Table 2, Mean maximum voluntary contraction (MVC), standard deviation (SD), intraclass correlation coefficient (ICC), smallest detectable difference (SDD) and normalized SDD (%SDD) for all measurements on 63 children.

Measurement	Mean	SD	ICC	SDD	%SDD
Thumb palmar abduction DOM (4-6)	16.8	4.72	0.94	3.2	19%
Thumb palmar abduction non-DOM (4-6)	15.4	4.51	0.95	2.9	19%
Thumb palmar abduction DOM (7-9)	24.7	4.84	0.93	3.6	15%
Thumb palmar abduction non-DOM (7-9)	23.1	5.44	0.95	3.3	14%
Thumb palmar abduction DOM (10-12)	35.0	6.79	0.93	4.9	14%
Thumb palmar abduction non-DOM (10-12)	33.2	7.48	0.96	4.4	13%
Thumb palmar abduction DOM (all)	**26.8**	**9.25**	**0.98**	**4.0**	**15%**
Thumb palmar abduction non-DOM (all)	**25.2**	**9.41**	**0.98**	**3.7**	**15%**
	Mean	**SD**	**ICC**	**SDD**	**%SDD**
Thumb opposition DOM (4-6)	33.8	8.52	0.95	5.5	16%
Thumb opposition non-DOM (4-6)	34.7	8.19	0.97	3.9	11%
Thumb opposition DOM (7-9)	48.9	9.98	0.97	4.8	10%
Thumb opposition non-DOM (7-9)	49.9	10.52	0.97	4.9	10%
Thumb opposition DOM (10-12)	57.3	9.78	0.94	6.7	12%
Thumb opposition non-DOM (10-12)	58.1	10.19	0.97	5.0	9%
Thumb opposition DOM (all)	**48.4**	**13.27**	**0.97**	**5.9**	**12%**
Thumb opposition non-DOM (all)	**49.3**	**13.46**	**0.98**	**4.7**	**9%**
	Mean	**SD**	**ICC**	**SDD**	**%SDD**
Thumb MCP flexion DOM (4-6)	35.3	8.19	0.97	4.1	12%
Thumb MCP flexion non-DOM (4-6)	34.7	8.00	0.98	3.2	9%
Thumb MCP flexion DOM (7-9)	47.6	8.37	0.93	6.2	13%
Thumb MCP flexion non-DOM (7-9)	46.9	9.18	0.98	4.1	9%
Thumb MCP flexion DOM (10-12)	57.2	7.89	0.93	5.7	10%
Thumb MCP flexion non-DOM (10-12)	56.0	8.94	0.96	5.0	9%
Thumb MCP flexion DOM (all)	**48.3**	**11.85**	**0.97**	**5.7**	**12%**
Thumb MCP flexion non-DOM (all)	**47.4**	**12.15**	**0.98**	**4.3**	**9%**
	Mean	**SD**	**ICC**	**SDD**	**%SDD**
Index finger abduction DOM (4-6)	15.8	3.30	0.92	2.6	16%
Index finger abduction non-DOM (4-6)	15.0	3.50	0.88	3.4	23%
Index finger abduction DOM (7-9)	21.2	3.28	0.88	3.1	15%
Index finger abduction non-DOM (7-9)	19.8	2.95	0.80	3.7	19%
Index finger abduction DOM (10-12)	26.5	3.97	0.84	4.5	17%
Index finger abduction non-DOM (10-12)	25.9	4.78	0.93	3.6	14%
Index finger abduction DOM (all)	**22.0**	**5.54**	**0.94**	**3.7**	**17%**
Index finger abduction non-DOM (all)	**21.0**	**5.86**	**0.95**	**3.5**	**17%**
	Mean	**SD**	**ICC**	**SDD**	**%SDD**
Little finger abduction DOM (4-6)	8.6	1.81	0.80	2.2	25%
Little finger abduction non-DOM (4-6)	7.9	1.43	0.61	2.5	31%
Little finger abduction DOM (7-9)	10.7	2.26	0.77	3.0	28%
Little finger abduction non-DOM (7-9)	9.5	1.78	0.72	2.6	27%
Little finger abduction DOM (10-12)	14.6	3.26	0.84	3.6	25%
Little finger abduction non-DOM (10-12)	14.0	3.52	0.89	3.3	23%
Little finger abduction DOM (all)	**11.7**	**3.59**	**0.90**	**3.1**	**27%**
Little finger abduction non-DOM (all)	**10.9**	**3.65**	**0.92**	**2.8**	**26%**

Figure 2, Bland-Altman plots of the mean maximum voluntary contraction (MVC) of the dominant hand using the RIHM versus the difference between the MVC in test and retest. In order: thumb abduction, thumb opposition, thumb MCP flexion and abduction of the index and the little finger.



Discussion

The aim of our study was to test the reliability of the RIHM in children (4 -12 years old). Reliability values of children found in this study were comparable to values of the RIHM in adults.(10-11) For children the ICC's were 0.98 for abduction of the thumb and 0.97 for opposition of the thumb. For the reliability of the abduction of the index and little finger we noted ICC values of at least 0.94 for the index finger and 0.90 for the little finger.

Since ICC's are not only determined by measurement error but also by between-subject variation, ICC values in literature are difficult to compare.(17) The same influence of between-subject variation on ICC values may also explain why all three age groups, with lower between-subject variation than for the total group, had lower ICC's than the ICC of the total group.

A good comparison of reliability can be made using the (normalized) SDD. The normalized SDD's were between 9% and 31%, with the thumb measurements showing the lowest normalized SDD's of 9% to 15%. The measurements on the index finger were slightly less reliable (17%) and the little finger was the least reliable (26%). The SDD's are comparable to those found in adults, with adults showing normalized SDD values of 18% to 27%.(10-11) Comparing the reliability in children of the RIHM to a Jamar-like dynamometer, the RIHM seems slightly more reliable with normalized SDD's of 9% - 26% compared to 19% - 27% for a Jamar-like dynamometer.(9)

There are some limitations to our study. First, because this study was performed only in children without impairment of the upper limb, no conclusion can be drawn on the reliability in children with impairments. Furthermore, in some cases the interval between the test and the retest was relatively long (range, 7-46 days; average, 26 days). However, no overall increase in strength was found in the retest measurement, a finding illustrated by the evenly distribution of the data around the zero-difference line for all age groups (Figure 2). This suggests that the interval between measurements was not long enough to allow a systematic improvement in strength in the retest measurements.

Some problems need to be considered when measuring children. Because of their lower attention span a break-test may be more difficult to perform, because it involves the subject holding a static position that the examiner tries to "break" (change) through force exertion. The instruction to hold a finger in place may be less interesting then trying to move an object. However, it should also be noted that the break-test has the advantage that it is easy to instruct the children (‘maintain you position’) and that the examiner can easily determine whether the children create the force in the appropriate directions.

In most clinical practices hand motor function is evaluated by measuring grip strength. Grip strength is a combination of both extrinsic and intrinsic hand muscles. No specific conclusions can be drawn on the function of intrinsic hand muscles when using grip strength devices like the Jamar handheld dynamometer. However intrinsic muscle function can play an important role in different congenital hand malformations, like hypoplasia or dysplasia of the fingers or thumb.

One specific example of a patient group in which the RIHM may add useful information to the assessment of hand function is in patients with congenital hand malformations. For children with congenital hand malformations who are treated very early in their life, it is very important to receive the right therapy. Measuring both intrinsic and extrinsic hand muscles is important in order to get a growing child close to development of children with normal hand function. Because strength measurements of individual fingers and thumb were found to be reliable we recommend including such measurements when evaluating interventions. Measuring strength of the individual fingers and the thumb can provide a more complete picture of hand function when diagnosing and evaluating hand problems. Therefore testing with the RIHM will add great value to better understand the role of the muscle strength of the individual fingers and thumb in relation to hand function and other grip tests.

Chapter 5

Reliability on hand strength measurements using the Rotterdam Intrinsic Hand Myometer (RIHM) in children

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Reference values on the Rotterdam Intrinsic Hand Myometer (RIHM) in children - Clinical Orthopaedics and Related Research: (2010 -Provisionally accepted)

Chapter 6

Reference values on the Rotterdam Intrinsic Hand Myometer (RIHM) in children

Abstract

Background: When treating patients with, e.g. congenital malformation, neurodegenerative diseases or trauma of the hand, measuring grip strength does not give a complete picture of a patient's hand strength. The Rotterdam Intrinsic Hand Myometer (RIHM) can add valuable information by measuring the strength of the individual fingers or thumb.

Purpose: The aim was to present reference values of children on the RIHM in an intuitive and easy way by creating growth diagrams for finger- and thumb strength.

Patient and Methods: In 101 children (4-12 years) using the RIHM, we measured thumb palmar abduction, thumb opposition and thumb flexion in the metcarpo phalangeal joint as well as abduction of the index- and little finger. In addition, we determined hand-dominance, gender, height and weight. All measurements were performed in a randomized order by the same researcher.

Results: We developed statistical models for drawing growth curves using estimated centiles for each individual strength measurement. Separate models for dominant and nondominant hand of boys and girls were developed as well as a combined model. Because there was no significant difference in strength between boys and girls and between dominant and non dominant hand, we combined those for each growth diagram.

Conclusions: In this study, we introduced growth diagrams therefore present the five different measurements. These diagrams can be applied in certain pediatric patient groups (congenital malformations, neuromuscular disorders) where the RIHM can add useful information for the assessment of hand function, while allowing tracking of multiple strength measurements of a growing child over time.

Introduction

Important motor skills of the hand are the power grip, key grip and pinch grip(1). Generally, motor skills of the hand are regulated using both intrinsic and extrinsic muscle groups. In case of grip or pinch strength, a combination of extrinsic and intrinsic hand muscles strength is used, while a large number of joints are involved. However, some movements of the hand, such as abduction or adduction of the fingers or abduction or opposition the thumb, are regulated predominantly by intrinsic hand muscles.

While regular instruments for measuring hand function, such as grip and pinch dynamometers, measure a combination of muscle groups and joints, they measure predominantly strength of the extrinsic hand muscles. However, it is often important to measure strength of specific thumb and hand movements to determine improvements after hand-related interventions. For example, direct measurement of opposition strength of a hypoplastic thumb after applying a specific tendon transfer to this thumb may provide more specific information than grip strength. The Rotterdam Intrinsic Hand Myometer (RIHM) is capable of measuring the strength of the individual fingers or thumb at a specific joint. Where grip and pinch measurements provide more general information, the RIHM is able to accurately measure strength development of very specific parts of the hand. Depending on the clinical setting, adding RIHM measurements to general grip or pinch measurements can be of great importance. Generally, when treating children whose hand function is affected, accurately monitoring their finger strength development over time provides insight into their impairment.

In previous studies, the RIHM has proven to be reliable in both adults and children. The RIHM has already been tested on inter rater and intra rater reliability in patients with Charcot–Marie–Tooth disease and was found to be very reliable(2). Furthermore the RIHM has already been proven to be reliable with high intra rater reliability in healthy children(3) and in healthy and affected adult populations(4-5). However, at present, no reference values have been presented for the strength of individual fingers and thumb in different directions. Since reference values presented in a classical table format are difficult to use, an alternative would be to use a growth diagram in which strength is plotted against age. This approach to reference values in children would allow for easier discrimination between the effects of growth, neuromuscular maturation and those of the intervention. Using growth diagrams where an increase or decrease of strength can be easily plotted over time facilitates an intuitive and easily interpretable way of using reference values, while variation in strength can be accounted for using the correct percentiles. Similar growth diagrams for length and weight are widely used at infant welfare centers across the world(6-8). In addition, we recently developed these same diagrams for grip strength(9). These strength development diagrams give an immediate indication of the strength that can be expected at the child's age using a continuous age scale, in contrast to reference tables with a 1-year or 2-year intervals.

The aim of this study was to present reference values of the individual finger and thumb strength, measured with the RIHM, in an intuitive and easily accessible way. Besides presenting reference values in a classical table format, we will present our data in the form of growth diagrams, accompanied with the centiles to project the variation between subjects.

Material & Methods

Subjects

After approval of the Institutional Review Board and after informed consent of the parents, children from a local primary school without upper limb impairment were approached for participation. Hand dominance and upper extremity problems that could influence hand strength were determined by evaluating parents' responses to a questionnaire. Children with a history of upper extremity trauma or abnormalities were excluded. A total of 101 children, between 4 and 12 years old, were included in this study. Of all the children, 94% were right-handed (Table 1).

Table 1, Number of participants divided among gender and age.

Age (years)	Boys (n)	Girls (n)	Total
4	6	2	8
5	3	5	8
6	5	8	13
7	6	5	11
8	4	9	13
9	10	4	14
10	5	8	13
11	5	9	14
12	5	2	7
Total	**49**	**52**	**101**

Material

The Rotterdam Intrinsic Hand Myometer (RIHM; Figure 1) is a dynamometer that measures strength by means of muscle resistance in a break-test. This break-test is performed while pulling with the RIMH at an easily controllable angle(10). The examiner and subject are seated opposite to each other at a table and the subject is shown and instructed how to keep their finger or thumb in place. Slowly, while the subject is instructed to hold its position, force is increased and after a few seconds the examiner pulls to "break" the position. We have previously shown that the RIHM can reliably measure the different muscles in the hand in children(3): The ICC values for a group of children (4-12 years old) are > 0.97 for the thumb measurements, > 0.94 for the index finger and > 0.90 for the little finger when analyzed for the whole group, while no relation was found between age and reliability(3).

Figure 1, The Rotterdam Intrinsic Hand Myometer (RIHM) measurement of radial abduction of the index finger.

Measurements

In this study we focused on strength measurements of the thumb, index finger and little finger, because the thumb together with the index- and little finger form the outer anatomical boundaries for different prehesion functions of the hand. We measured abduction of the index finger (initiated by the first Dorsal Interosseous muscle) and little finger (initiated by abductor digiti quinti muscle). In addition, for the thumb, we measured thumb palmar abduction (primarily the Abductor Pollicis Brevis muscle), thumb opposition (primarily the Opponens Pollicis muscle) and thumb flexion in the metcarpo phalangeal joint (primarily the intrinsic Flexor Pollicis Brevis muscle). The measurements were repeated 3 times and the mean of the 3 tests was registered. After each measurement the dynamometer was reset. All measurements were performed in a randomized order by the same researcher (HMM).

Statistical methods

To develop the growth curves, we first estimated the centiles for each strength measurement using Altman's method of absolute scaled residuals(11). Because visual inspection did not reveal skewness or non-normal kurtosis we decided not to transform the dependant variable. In a first model, strength was modeled as a function of the age. To allow for nonlinearity in the mean, we used restricted cubic splines with three knots placed at the 10th, 50th, and 90th centiles. The standard deviation was estimated using the regression function of the absolute residuals. We estimated separate relationships for boys and girls for both the dominant and nondominant hands.

The before-mentioned model of strength versus age was compared with a more complex model that also included weight and length. All factors were included in this more complex model as a restricted cubic spline with three knots. Residuals of the various models were checked for normality and serial correlation.

To test for significantly strength differences between both genders and between the dominant and non-dominant hand, we used a partial-F test. Because we only found a significant difference between both hands for one of the five measurements (see Results), we used the measurements of both hands for developing combined diagrams. Following the same reasoning, we combined all measurements for both boys and girls as no significant difference in strength between both genders was found (also see Results). Although separate diagrams for each gender would create the most accurate model for predicting finger strength, we found that an easily interpretable combined diagram for each measurement resulted in only a minor decrease in the goodness of fit (R2) of the model (see Results). All estimations and calculations were done using SAS 9.1.

Results

Tables 2-6 present all data in a classical table format, where finger strength is reported for the dominant and non-dominant hands for all children between four en twelve years clustered per one-year age group. Grip strength generally increased with age in all measurements. We found no significant differences in finger strength between boys and girls in any of the muscle groups measured. When comparing the dominant and nondominant hand we only found a significant difference ($P < 0.001$) for thumb palmar abduction.

Table 2, Thumb Palmar abduction strength in Newton: Mean of the MVC, Standard Deviation (SD), Minimum MVC (Min) and Maximum MVC (Max)

	Age	N	Mean	SD	Min	Max
Dominant	4	8	14.4	3.9	7.6	19.3
Nondominant			13.0	3.6	7.6	17.9
Dominant	5	8	17.7	5.5	9.8	25.7
Nondominant			14.9	3.5	9.1	18.9
Dominant	6	13	18.1	4.2	12.3	25.6
Nondominant			17.6	3.2	13.9	23.3
Dominant	7	11	22.7	6.4	10.9	34.2
Nondominant			21.3	5.4	11.8	32.3
Dominant	8	13	25.0	4.9	16.7	34.1
Nondominant			23.7	5.3	16.6	33.7
Dominant	9	14	28.6	5.7	19.1	39.6
Nondominant			27.9	6.5	19.1	39.4
Dominant	10	13	31.2	3.2	27.1	38.1
Nondominant			28.6	3.7	23.0	34.3
Dominant	11	14	35.8	8.9	22.2	55.4
Nondominant			33.7	9.3	21.0	58.7
Dominant	12	7	36.2	6.1	28.5	46.5
Nondominant			30.2	6.7	21.5	36.7

Table 3, Thumb Opposition strength in Newton: Mean of the MVC, Standard Deviation (SD), Minimum MVC (Min) and Maximum MVC (Max)

	Age	N	Mean	SD	Min	Max
Dominant	4	8	28.9	7.2	18.6	39.3
Nondominant			30.2	6.0	20.4	37.3
Dominant	5	8	29.9	7.4	17.3	38.3
Nondominant			32.5	8.2	20.2	45.1
Dominant	6	13	38.2	7.7	24.6	51.6
Nondominant			38.6	7.0	27.5	50.5
Dominant	7	11	43.0	5.8	29.3	51.6
Nondominant			42.8	5.9	33.7	51.7
Dominant	8	13	51.6	9.2	36.2	74.6
Nondominant			51.6	9.5	34.7	74.9
Dominant	9	14	53.6	6.5	45.2	63.5
Nondominant			54.1	8.7	43.7	65.2
Dominant	10	13	54.2	8.4	35.3	67.7
Nondominant			54.3	7.2	41.5	64.8
Dominant	11	14	58.0	9.7	43.2	75.1
Nondominant			59.5	11.2	39.1	77.4
Dominant	12	7	60.8	13.2	38.0	77.6
Nondominant			66.2	15.8	48.0	85.6

Table 4, Thumb flexion (MCP) strength in Newton: Mean of the MVC, Standard Deviation (SD), Minimum MVC (Min) and Maximum MVC (Max)

	Age	N	Mean	SD	Min	Max
Dominant	4	8	30.0	6.6	19.9	37.2
Nondominant			30.9	6.3	19.9	38.2
Dominant	5	8	31.1	7.6	17.6	37.8
Nondominant			30.5	7.2	17.5	40.2
Dominant	6	13	38.1	8.6	23.1	49.6
Nondominant			38.5	7.8	26.2	50.6
Dominant	7	11	43.3	7.8	31.0	54.5
Nondominant			41.5	7.3	31.6	54.2
Dominant	8	13	47.6	7.8	30.4	58.4
Nondominant			49.1	8.8	30.9	64.7
Dominant	9	14	54.0	7.9	42.9	70.1
Nondominant			53.7	7.5	43.2	69.1
Dominant	10	13	54.3	6.9	39.5	64.6
Nondominant			51.3	6.8	35.2	59.9
Dominant	11	14	58.3	8.5	45.9	73.3
Nondominant			60.9	8.5	43.5	72.0
Dominant	12	7	61.9	16.0	38.2	88.9
Nondominant			65.3	11.6	43.8	82.0

Table 5, Index finger abduction strength in Newton: Mean of the MVC, Standard Deviation (SD), Minimum MVC (Min) and Maximum MVC (Max)

	Age	N	Mean	SD	Min	Max
Dominant	4	8	14.1	4.4	7.5	20.3
Nondominant			12.7	3.2	8.4	17.7
Dominant	5	8	15.2	2.4	11.8	18.3
Nondominant			13.8	2.7	10.5	19.3
Dominant	6	13	16.8	3.2	11.8	22.8
Nondominant			17.1	2.8	13.7	22.1
Dominant	7	11	18.1	2.2	14.8	21.5
Nondominant			18.8	1.9	15.3	21.1
Dominant	8	13	21.5	2.7	17.1	26.3
Nondominant			20.5	3.1	17.3	28.6
Dominant	9	14	23.7	4.7	17.2	33.4
Nondominant			21.7	5.0	14.8	32.1
Dominant	10	13	25.1	3.9	15.6	29.7
Nondominant			24.0	4.5	15.3	30.2
Dominant	11	13	27.9	4.6	18.8	34.0
Nondominant			26.5	4.6	16.8	32.4
Dominant	12	7	25.2	4.2	17.5	30.0
Nondominant			29.4	4.3	24.4	35.8

Table 6, Little finger abduction strength in Newton: Mean of the MVC, Standard Deviation (SD), Minimum MVC (Min) and Maximum MVC (Max)

	Age	N	Mean	SD	Min	Max
Dominant	4	8	7.2	1.7	5.2	10.0
Nondominant			7.2	1.8	5.5	10.1
Dominant	5	8	8.3	1.4	6.6	11.0
Nondominant			7.6	1.4	6.0	9.9
Dominant	6	13	7.8	2.0	4.5	10.9
Nondominant			7.7	1.2	5.7	9.6
Dominant	7	11	10.1	2.3	7.4	14.2
Nondominant			10.3	2.1	7.0	14.0
Dominant	8	13	10.2	1.6	7.5	13.2
Nondominant			10.5	2.5	6.5	15.7
Dominant	9	14	12.8	2.7	9.5	18.8
Nondominant			12.2	3.4	7.9	17.2
Dominant	10	13	13.2	3.3	8.4	18.4
Nondominant			11.7	1.6	9.7	15.1
Dominant	11	14	14.8	2.7	9.5	19.9
Nondominant			14.9	3.2	9.5	20.3
Dominant	12	7	17.4	4.4	11.5	25.7
Nondominant			17.8	2.6	13.6	19.8

As there was no significant difference in strength found between boys and girls and between the dominant and non-dominant hand we chose to combine all the data for each specific measurement to create a model for predicting finger strength as a function of age. When comparing these models, we found that the complex model (including length and weight with separate models for both genders and both hands) differed in goodness of fit (R2) from the simple model (without age and weight and with genders and both hand combined) by, on average, 4% and maximally 8% (Table 7).

The statistical models for the relation between individual finger or thumb strength and age were converted into growth diagrams (Figures 2-6). Besides the curve of the population mean, these diagrams also show the centiles that correspond to each standard deviation added or subtracted from the mean: 2.5%, 16%, 50%, 84% and 97.5% centiles, corresponding to -2SD, -1SD, mean, +1SD and +2SD.

Table 7, The R2 of the possible models that can be used to draw growth curve. Shaded are the more complex models with age length and weight as variables, non-shaded are the simpler models with only age as the dependent variable. Values reported in the columns are for dominant and nondominant hand separately and those for the model with both hands included.

Boys	**Model**	**Dominant**	**Nondominant**	**Combined**
Thumb Palmar Abduction	Simple	0.59	0.50	0.54
	Complex	0.65	0.58	0.60
Thumb Opposition	Simple	0.63	0.65	0.63
	Complex	0.65	0.72	0.67
Thumb MCP Flexion	Simple	0.65	0.74	0.69
	Complex	0.68	0.78	0.72
Index Finger Abduction	Simple	0.59	0.60	0.59
	Complex	0.61	0.68	0.63
Little Finger Abduction	Simple	0.68	0.65	0.66
	Complex	0.71	0.67	0.69
Girls	**Model**	**Dominant**	**Nondominant**	**Combined**
Thumb Palmar Abduction	Simple	0.64	0.66	0.63
	Complex	0.65	0.73	0.66
Thumb Opposition	Simple	0.60	0.55	0.58
	Complex	0.66	0.60	0.63
Thumb MCP Flexion	Simple	0.56	0.56	0.56
	Complex	0.64	0.65	0.64
Index Finger Abduction	Simple	0.58	0.65	0.61
	Complex	0.61	0.71	0.65
Little Finger Abduction	Simple	0.48	0.53	0.50
	Complex	0.55	0.61	0.57
Boys & Girls combined	**Model**	**Dominant**	**Nondominant**	**Combined**
Thumb Palmar Abduction	Simple	0.61	0.57	**0.57**
	Complex	0.63	0.63	0.62
Thumb Opposition	Simple	0.59	0.57	**0.58**
	Complex	0.62	0.61	0.61
Thumb MCP Flexion	Simple	0.59	0.62	**0.60**
	Complex	0.61	0.66	0.63
Index Finger Abduction	Simple	0.57	0.62	**0.59**
	Complex	0.59	0.66	0.62
Little Finger Abduction	Simple	0.58	0.59	**0.58**
	Complex	0.61	0.62	0.61

Figure 2, Thumb Palmar abduction strength in Newton plotted against age in years. The centiles 2.5%, 16%, 50%, 84% and 97.5% are shown.

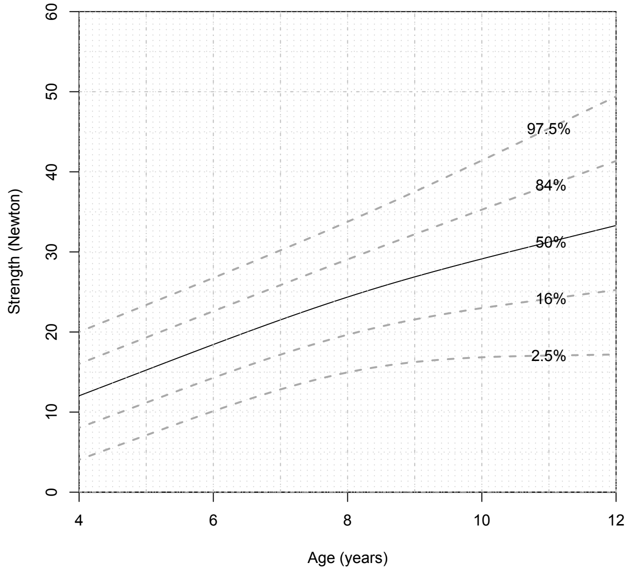


Figure 3, Thumb Opposition strength in Newton plotted against age in years. The centiles 2.5%, 16%, 50%, 84% and 97.5% are shown.

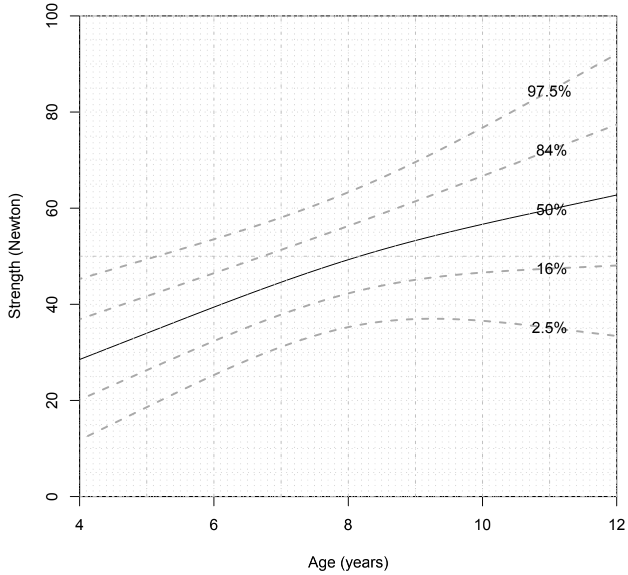


Figure 4, Thumb flexion (MCP) strength in Newton plotted against age in years. The centiles 2.5%, 16%, 50%, 84% and 97.5% are shown.

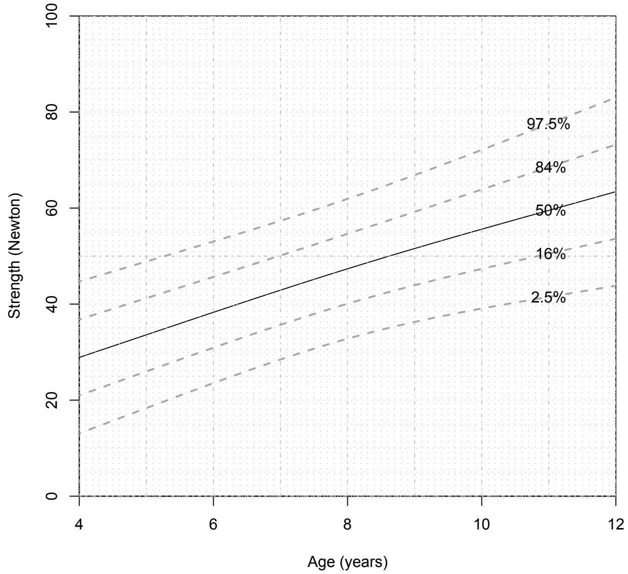


Figure 5, Index finger abduction strength in Newton plotted against age in years. The centiles 2.5%, 16%, 50%, 84% and 97.5% are shown.

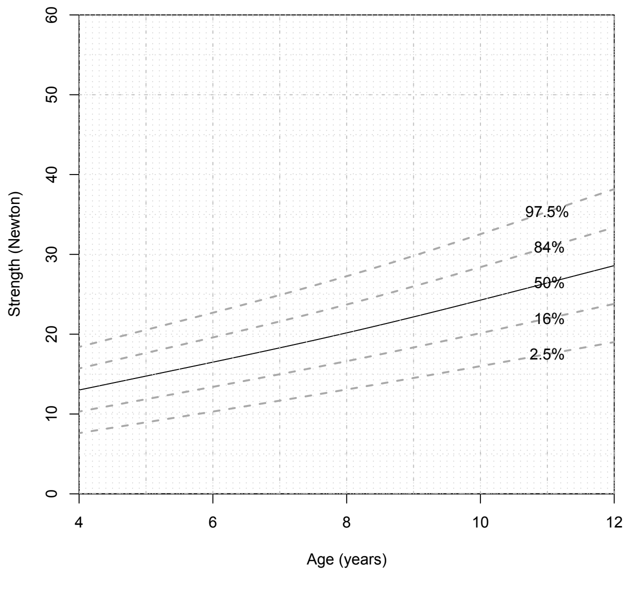
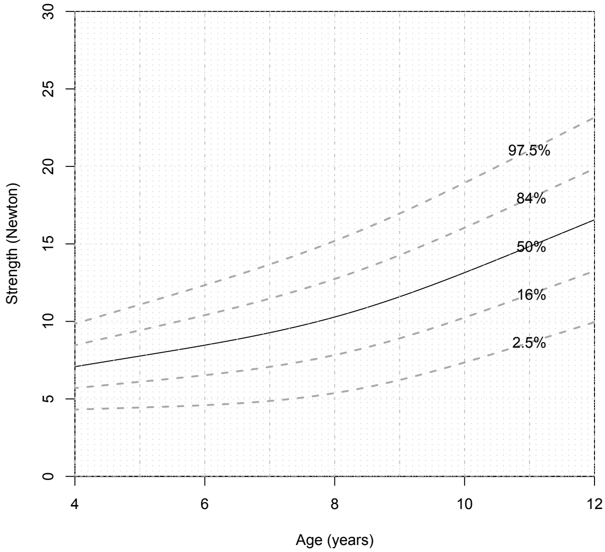


Figure 6, Little finger abduction strength in Newton plotted against age in years. The centiles 2.5%, 16%, 50%, 84% and 97.5% are shown.



Discussion

Our general aim in this study was to present reference values for individual finger and thumb strength using the RIHM in children. To present these reference values in an easily and intuitively understandable way, besides the classical table-format, we developed curves for finger and thumb strength in relation to age. These diagrams, shown in Figures 2 – 6, provide doctors and therapists with a tool to easily plot the development of finger and thumb strength over time.

By allowing a child's finger and thumb strength to be plotted over time, the diagrams show how grip strength of a child develops relative to the reference data contained in the diagram. If a child's strength is plotted at a certain distance from a centile line, a change in this distance at follow-up may indicate an increase or decrease in strength relative to his or her age. An additional advantage for individual patient measurements is that a table containing reference data would be difficult to use as such values are given per year or two-year interval. In contrast, the growth diagrams present a continuum in finger and thumb strength values, allowing measurement outcome to be compared with an age that corresponds more exactly.

There are some limitations to our study. We chose to omit variables such as length and weight from our model and just use age to predict strength. This approach resulted in 5 diagrams for each measurement. These diagrams combine both hands and genders and therefore do not acknowledge the effect of sex and hand dominance. Even though omitting weight, length, gender and hand dominance from the model resulted in a less accurate model, the goodness of fit of the model only marginally decreased (Table 7). The 5 diagrams presented only differ on average 4% with models that do distinguish between gender and hand-dominance. In our opinion, the benefit of using one single diagram for each measurement outweighs the small reduction in predictability of the model. Another limitation of this study concerns the study design. As we only examined individual strength measurements on one specific moment in time, the model that we provide is not calculated on follow-up measurements, an approach that would be more suitable but more difficult with respect to gathering the data. Furthermore, our population consisted of healthy, mostly Caucasian, children within the near vicinity of our research facility and they might not be representative for the children that might benefit from using such growth diagrams at follow up.

When comparing our diagrams on thumb and finger strength to similar growth diagrams or grip strength in children and diagrams used at children's welfare centers, we found that they show a similar form and shape(7-9). Since this is, to our knowledge, the first study on thumb and finger strength in children, the values reported in this study cannot be compared to other studies.

In conclusion, we hope the provided diagrams will motivate doctors and therapist to incorporate individual finger and thumb measurements into their daily practice when treating children with affected hand function. These diagrams will allow accurate study of the development of individual children. In this way, a possible effect of treatment or therapy may quickly be visible as change in the curve of the subject relative to the reference population.

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The added value of measuring thumb and finger strength when comparing strength measurements in hypoplastic thumb patients

Chapter 7

The added value of measuring thumb and finger strength when comparing strength measurements in hypoplastic thumb patients

Abstract

When interventions to the hand are aimed at improving function of specific fingers or the thumb, general grip and pinch measurements do not provide enough detailed information to assess the strength of involved joint. In patients with thumb hypoplasia the Rotterdam Intrinsic Hand Myometer (RIHM) is able to assess the success of interventions specifically aimed at thumb function such as tendon transfers or pollicisations for improving opposition. 40 patients diagnosed with thumb hypoplasia were included in this study (age range 4-31 years). 65 affected hands were assessed using grip, pinch and RIHM measurements, Blauth classified as 1 type I, 24 type II, 7 type IIIA, 8 type IIIB , 15 type IV and 10 type V hands. Radial Longitudinal Deficiency (LRD) classification according to Bayne and Klug et al. was simplified in to two separate groups with either a mild (type I+II) or a severe (type III+IV) LDR. 34 hands did not have a LDR, whereas 16 hands were associated with mild type and 15 hands with severe type LDR. Of the total 65 hands, 54 hands had been operated, of which 18 Blauth II, 6 Blauth IIIA, 8 Blauth IIIB, 15 Blauth IV and 7 Blauth V. Operations performed were 21 "Flexor Digitorum Superficialis of the fourth finger" (FDS4) tendon transfers for opposition and MP joint instability, with or without 1st web deepening; 16 abductor digiti quinti transfers for opposition and 28 pollicisations. Besides grip, tip pinch, tripod pinch and key pinch we used Rotterdam Intrinsic Hand Myometer to measure thumb palmar abduction and thumb opposition. In addition we measured abduction of the index finger and little finger.

For the mild and severe LDR patients combined, grip and pinch strength as well as palmar abduction and thumb opposition were significantly lower than references values ($P < 0.001$). However, strength in the index finger abduction and the little finger abduction was not decreased.

All strength values decreased with increasing Blauth type. Blauth type II hands (n=15) that received a FDS4 to improve opposition and metacarpo phalangeal (MCP) joint stability, compared to non operated Blauth type II hands (n=6), showed a lower grip strength (p=0.019) but the same group showed a trend towards a higher opposition strength (p=0.094). Overall, the combined set of strength measurements was able to draw an appropriate picture of hand strength in a patient group with thumb hypoplasia. Using the RIHM, we were able to illustrate strength patterns on a finger-specific level, showing the added value of the RIHM when evaluating outcome in patients with hand related problems.

Introduction

Thumb hypoplasia can vary from a smaller less powerful thumb to total absence of the thumb. Thumb hypoplasia can be classified according to Blauth in five different types and can be accompanied by Radial Longitudinal Deficiency (LDR) (see table 1) (1-2). Interventions in hypoplastic thumb patients can vary from improving range of motion by widening the 1st web-space or improve joint stability and increase strength with tendon transfers to complete pollicisation of the index. One of the tools to assess these interventions are hand strength measurements. To assess different muscle functions in the hand, different types of strength measurements are needed. For example, grip strength measurement in patients with thumb hypoplasia may not be able to assess the success of interventions specifically aimed at thumb function such as tendon transfers for improving opposition or pollicisation.

Table 1 Blauth type distribution of the patient group. Blauth type classification: Modified classification by Manske and McCarroll

Blauth type classification	Modified classification by Manske and McCarroll	Number hands
Type I	Minor hypoplasia of the whole thumb compared to contra lateral	1
Type II	Adduction contracture of the first web space, MCP joint instability, Thenar muscle hypoplasia	24
Type IIIA	Same abnormalities as in Type II, Extrinsic muscle hypoplasia, Hypoplastic first carpometacarpal	7
Type IIIB	Same abnormalities as in Type IIIA, Aplasia of the first carpometacarpal joint	8
Type IV	Floating thumb	15
Type V	Absent thumb	10

Strength measurements of the hand are generally performed using grip and pinch dynamometers. While grip and pinch strength measurements are reliable in children and adults (3-10) and evaluate relevant functions of the hand, they cannot specifically evaluate strength of the thumb and fingers in isolation. Therefore, they may not be sensitive enough to assess hand function in patients with a hypoplastic thumb. For example, patients with a hypoplastic thumb type IV or V or patients with an immobile stiff thumb may be able to exert a high grip force while their thumb strength is negligible.

To overcome this lack of sensitivity, there is a need to assess outcome of interventions on a finger-specific level.

The Rotterdam Intrinsic Hand Myometer (RIHM) has the ability to measure individual finger and thumb strength, such as thumb opposition, palmar abduction of the thumb and abduction of the index and little finger. The RIHM was found to be reliable in both healthy children and adults. Furthermore, reference values for children and adults are available. (11-13) The added value of the RIHM to the grip and pinch dynamometer has been reported in patient groups with peripheral nerve injury (11), Charcot Marie Tooth (14), and carpal tunnel syndrome (15). However, this instrument has never been applied in patients with congenital hand deformities. Because individual fingers are often affected in congenital hand malformations, use of the RIHM, in addition to regular grip and pinch measurements, might possibly result in more specific diagnostic information.

The aim of this study was to evaluate the spectrum of different strength measurements, such as pinch dynamometers, grip dynamometers and the RIHM in patients with a hypoplastic thumb. Additionally, the aim was to determine if the RIMH would be able to assess different aspects of hand strength compared to general pinch and grip strength in a group of hypoplastic thumb patients.

Material & Methods

Subjects

After approval of the Institutional Review Board and after informed consent of the patients and parents of the children, a total of 40 patients diagnosed with thumb hypoplasia were included in this study. The patient's age ranged between 4-31 years. Of these 40 patients, 65 affected hands were assessed using grip, pinch and RIHM measurements. Using the Blauth classification modified by Manske and McCaroll(16), we included 1 hand with type I, 24 hands with type II, 7 hands with type IIIA, 8 hands with type IIIB, 15 hands with type IV and 10 hands with type V. Presence of Radial Longitudinal Deficiency (LDR) was described using the classification according to Bayne and Klug(1). 34 hands did not have LDR, whereas 12 hands were associated with type I, 4 hands with type II, 3 hands with type III and 12 hands with type IV LDR. Of the total 65 hands, 54 hands had been operated, of which 18 Blauth II, 6 Blauth IIIA, 8 Blauth IIIB, 15 Blauth IV and 7 Blauth V. Operations performed were 21 Flexor Digitorum Superficialis of the fourth finger (FDS4) tendon transfers for opposition and metacarpo phalangeal (MCP) joint instability, with or without 1st web deepening; 16 abductor digiti quinti transfers for opposition and 28 pollicisations.

We simplified the LDR classification. Radial deficiency type according to Bayne et al. (1) is classified in 4 categories. We divided the five categories for LDR in two separate groups with either a mild or a severe LDR. In this classification, type I and II are considered "mild", whereas longitudinal radial dysplasia type III and IV are described as "severe".

Strength measurements

All measurements were performed in a randomized order by the same researcher (HMM). A mean of three maximum voluntary contractions was recorded for each hand. When one of the measurements showed a difference of more than 10% with the other measurements, that measurement was disregarded and a fourth measurement was added. The mean of 3 remaining maximum voluntary contractions (MVC's) was recorded for each hand. All children were seated in an appropriately adjusted chair during the measurements.

For grip strength we used a Lode dynamometer (Lode BV, Groningen, The Netherlands) (Figure 1), which is an electronic dynamometer comparable to the Jamar dynamometer. It operates similar and is calibrated to measure the same outcome as the Jamar dynamometer but is more accurate than the hydraulic Jamar, especially in the lower strength ranges. In a previous study, we quantified the measurement error of this instrument in children and found the Lode dynamometer to be reliable in healthy children from 4-12 years old. We also found that reliability increased with age and that children of 12 years old had similar reliability as adults.(4-6, 8, 17) The Lode dynamometer was used as recommended by the American Society of Hand Therapists: the subject sat with the shoulder adducted and the arm at the side of the body, the elbow flexed in a 90-degree angle, and the wrist in a neutral position.(18) We used the Lode dynamometer with the handlebar in position 2 for all hands to maximize the comparability between subjects.(19)

Pinch strength was measured using the same electronic console as used for grip strength. This console was linked to a pinch gauge to measure tip pinch, tripod pinch and key pinch (Figure 1). Before the start of each measurement, the subject was told to "squeeze as hard as you can!"

Figure 1 – Illustration of all strength measurements: Grip strength dynamometer (top row left), pinch strength dynamometer (top row right) and the Rotterdam Intrinsic Hand Myometer (RIHM) for measuring thumb palmar abduction (mid row left), little finger abduction (mid row right), thumb opposition (bottom row left),) and index finger abduction (bottom row right).

The Rotterdam Intrinsic Hand Myometer (RIHM; Figure 1) was used to measure the strength of the thumb, index finger and little finger. The RIHM is a dynamometer that measures strength by means of muscle resistance in a break-test. This break-test is performed while pulling with the RIHM at an easily controllable angle.(20) The examiner and subject are seated opposite to each other at a table and the subject is shown and instructed how to try to maintain their finger or thumb in the same position. Slowly, while the subject is instructed to hold position, force is increased and after a few seconds the examiner pulls to "break" the position. We have previously demonstrated that the RIHM can reliably measure the breaking strength of the palmar abduction, thumb opposition, and index finger and little finger abduction in the hand in children(13). In a recent study on the reliability of the RIHM, we found that the intraclass correlation coefficients (ICC's) of the RIHM for a group of children (4-12 years old) were > 0.97 for the thumb measurements, > 0.94 for the index finger, and > 0.90 for the little finger when analyzed for the whole group. No relation was found between age and reliability.(13) For adults the reliability of the RIHM in peripheral nerve injured patients was > 0.94 for all measurements. (11-12)

In this study, we used the RIHM to measure thumb palmar abduction (primarily the Abductor Pollicis Brevis muscle) and thumb opposition (primarily the Opponens Pollicis muscle). In addition we measured abduction of the index finger (initiated by the first Dorsal Interosseous muscle) and little finger (initiated by Abductor Digiti Quinti muscle). (11) For each measurement the RIHM was held at the correct perpendicular angle for the appropriate measurement, reckoning with a possible presented abnormal anatomical position to the upper limb and hand.

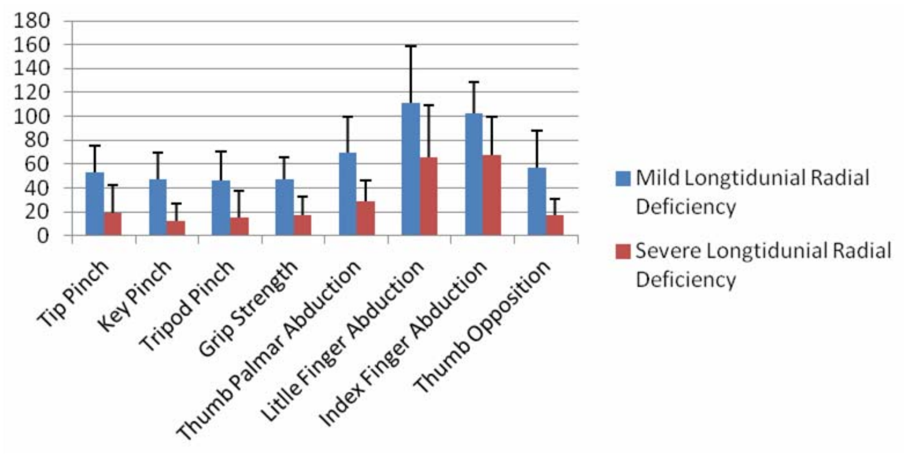
Statistical Methods

To compare between the different strength measurements, we normalized all strength measurements as a percentage of the reference values based on the exact age of the subjects.(21-26) Since normative data were absent between 12 year olds and adults, we used linear regression to fit the lacking values between the normative data of children and adults. For relating different strength measurements we used Pearson's correlation coefficient and we used T-tests to compare groups using SPSS statistics version 16.

Results

When comparing the normalized strength values for the different strength measurements, a number of important differences between the measurements can be seen. For the mild and severe LDR patients combined, grip and pinch strength measurements as well as the palmar abduction and opposition of the thumb were significantly reduced compared to the references values ($P < 0.001$). However, this strength decrease was not present for the RIHM measurements of the index finger abduction and the little finger abduction, indicating that not all hand muscle strength in these patients is decreased. When comparing the mild and severe LDR patients, we found that all measurements were able to detect a significant strength differences between both groups ($p < 0.001$) except for the index finger abduction strength ($P = 0.09$) (see Figure 2).

Figure 2 - Force levels expressed as percentage of reference values of healthy individuals (Y-axis), divided into mild (type 1,2) and severe (type 3,4) Radial Longitudinal Deficiency. Error bars indicate the standard deviation of the measurements. The X-axis represents the different strength measurements.



When comparing the different strength measurement between patients with different Blauth types, generally, strength decreased with increasing Blauth type (Figure 3). Again, higher values were found for the abduction of the index and little fingers of the patients with Blauth types of IV and V compared to the other strength measurement. Furthermore, Figure 3 indicates that grip and pinch strength decrease up till Blauth types 4 and 5, and thumb opposition decreased with increasing Blauth type.

Figure 3, Spider graph showing all strength measurements clustered per Blauth type. The spokes illustrate the force strength as a percentage of the reference values. The center of the graph indicates the lowest strength; the outer sides of the spokes indicate the highest strength (150% of reference values). On the left the results of the more traditional measurements are shown, on the right the RIHM measurements.

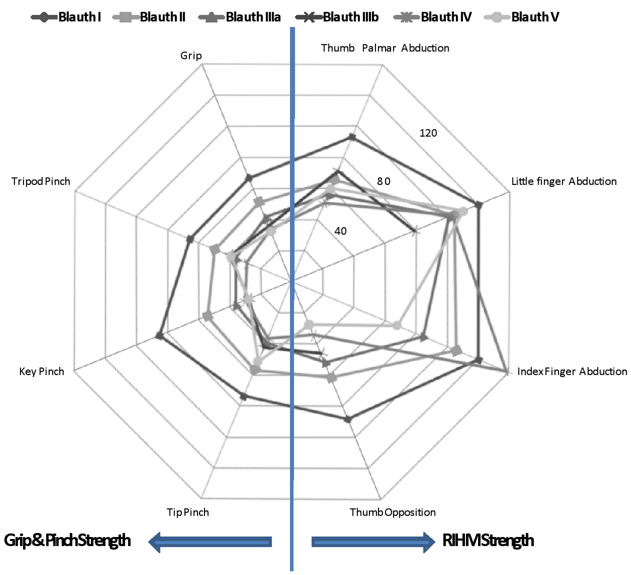


Table 2 shows the correlations between the different strength measurements. While most measurements were significantly correlated, the magnitude of the correlations demonstrated important differences. Overall, the correlations were the highest amongst the different pinch measurements and slightly lower between grip and pinch strength. Correlations amongst the different RIHM measurements and between the RIHM, grip, and pinch measurements were more diverse, ranging from 0 to 0.55.

Table 2, Correlations between different strength measurements. Legend: Pinch = pinch, Key = key pinch, Tripod = Tripod pinch, Grip = grip strength, Palmar = Thumb palmar abduction, Dig5 = Little finger abduction, Dig2 = Index finger abduction, Opp = Thumb opposition.

	Pinch	Key	Tripod	Grip	Palmar	Dig5	Dig 2	Opp
Pinch	1							
Key	0.70^{**}	1						
Tripod	0.85^{**}	0.64^{**}	1					
Grip	0.63^{**}	0.59^{**}	0.48^{**}	1				
Palmar	0.58^{**}	0.53^{**}	0.58^{**}	0.46^{**}	1			
Dig5	0.54^{**}	0.45^{**}	0.50^{**}	0.24	0.47^{**}	1		
Dig 2	0.37^{*}	0.39^{*}	0.19	0.31	0.12	0.43^{*}	1	
Opp	0.43^{**}	0.59^{**}	0.48^{**}	0.42^{**}	0.55^{**}	0.30^{*}	-0.03	1

* = Correlation is significant ($P < 0.01$); ** = Correlation is significant ($P < 0.05$)

Two of the correlations are further detailed in Figure 4. Figure 4A illustrates a relatively strong and linear relation between grip and pinch strength. In contrast, the correlation between grip strength and thumb opposition (Figure 4B) is not only lower, but also more non-linear with large differences between the different strength measurements for some patients. For example, patients in the lower right part of Figure 4B have high grip strength (±60-80% of the reference data) but a low thumb opposition force (±10%).

Figure 4, Correlations between grip strength (on the x-axis in both graphs) and tip pinch strength (left) or thumb opposition (right). Figure 4a shows a higher correlation between tip pinch and grip strength. Figure 4b shows a much lower correlation between grip strength and thumb opposition, illustrated by the wider horizontal spread of points in the scatter plot.

Figure 4a

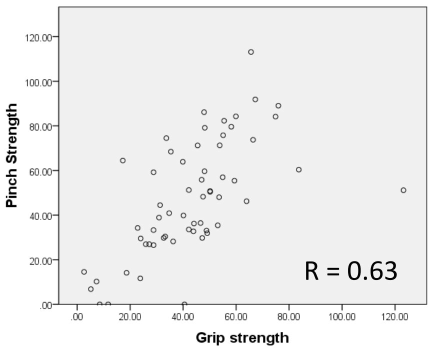
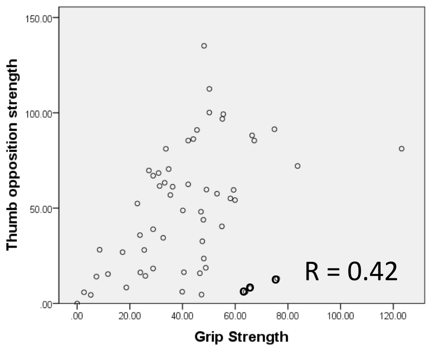
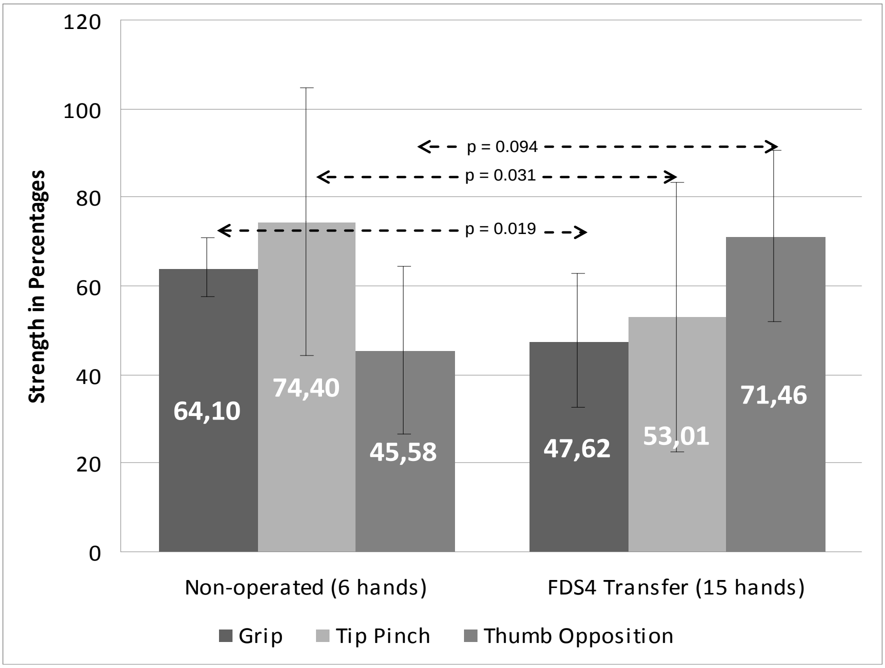


Figure 4b



Finally, we evaluated the ability of grip strength and RIHM measurements of thumb opposition to detect differences between non-operated Blauth type 2 thumbs (n=6) and operated Blauth type 2 thumbs (n=15) who received a tendon transfer of the FDS4 to improve opposition and MP joint stability. Both patient groups had no LDR. When comparing both groups, we found that grip strength was significantly lower in the FDS4 transfer group (p=0.019). However, when directly measuring thumb opposition, a trend towards a higher opposition strength (p=0.094) was found in the FDS4 transfer group (Figure 5).

Figure 5, Grip strength, Tip pinch strength and thumb opposition strength (Y-axis) for non operated hands (n=6) and hands that received an FDS4 transfer (n=15). Error bars indicate the standard deviation of the measurements. Strength for the non-operated hands was significantly higher compared to the hands that received FDS4 transfer with respect to Grip strength and Tip pinch.



Discussion

The aim of the study was to obtain discriminative information from different hand strength instruments, including the Rotterdam Intrinsic Hand Myometer (RIHM), when assessing hand function in patients with thumb hypoplasia. The goal was not to evaluate general outcome in these patients or to evaluate the different interventions used in these patients. As the different hand strength measurements were previously tested and validated in the hands of unaffected children the obvious next step was to test the strength measurements in children with congenital differences.

While traditionally outcome of hand surgery is qualitatively scored using terms as 'excellent', 'good' and 'poor', in the recent years, outcome assessment has increasingly focused on objective and validated instruments for hand function, such as strength dynamometers, goniometry, sensibility, and questionnaires or tests for evaluating activity and participation limitations. The also applies for studies on patients with hypoplastic thumbs, were outcome is also generally scored qualitatively and were hand strength is quantified using strength dynamometers to quantify outcome.(27-28) When comparing our results with the literature, we found that our grip and pinch strength values were between 40-47% of healthy reference values, which is quite similar to values of 40% found in literature.(28)

In a number of studies, it has been shown that instruments such as the RIHM can add to our understanding of pathological hand function and to the evaluation of outcome since it quantifies different aspects of hand function. For example, Schreuders et al. studied outcome after median and ulnar nerve injuries in adults and found that while grip strength recovered to 83% of the uninjured hand. However, the RIHM measurements revealed a poor recovery of, especially, the ulnar nerve innervated muscles (26 to 37%) when specifically testing the intrinsic muscle seperately.(11) Similarly, in patients with Charcot-Marie-Tooth, Selles et al. showed the added value of the RIHM in patients by indicating that high grip and pinch strength could be found in patients with severe intrinsic muscle weakness.(14) In addition, the RIHM correlated more strongly with the Sollerman hand function test than grip and pinch strength.(14) Finally, Geere et al. reviewed hand strength measurements in patients after carpal tunnel syndrome and acknowledged that the RIHM may be a more specific tool to test the thenar muscles than traditional tools. (15)

A number of findings in the present study indicates that the RIHM also has added value for evaluating hand strength in hypoplastic thumb patients. One such finding is that while grip strength, pinch strength and thumb strength were decreased compared to reference values, abduction strength of the index finger and little finger did not decrease. This illustrates that the RIHM is able to discriminate strength between specific muscle groups. Several patients had index finger and little finger abduction strength larger than 100% of the reference values which may even indicate mechanisms of compensation for the lack of thumb dexterity in these patients.

The relatively low correlations between some of the strength measurements and the non-linear relation between grip strength and thumb opposition strength also illustrate that the different measurements provide essentially different information about hand strength. More specifically, our data demonstrates that while grip strength and pinch strength often show similar values in the same patients, RIHM measurements demonstrated that thumb opposition can be very weak in patients with a strong grip. Since thumb opposition is essential for firm grasping and locking an object in the hand, and since intervention is therefore often aimed at improving opposition, the added value of RIHM to measure this function may be of great value to assess these patients.

In Figure 5 we compare hypoplastic thumb patients with and without an FDS4 tendon transfer to stabilize the MP joint and to reconstruct opposition. When only evaluating grip strength, the results may have suggested that hand function had decreased in these patients. However, RIHM measurement of thumb opposition, the main focus of the intervention, shows an important increase in strength in the operated hands. Even though we acknowledge that it is difficult to directly compare these two groups, this again illustrates the added value of the RIHM for measuring hand strength in these patients in addition to the traditional instruments.

There are some limitations to our study. The RIHM was found reliable in a healthy population of children, but was not tested for reliability in patients with thumb hypoplasia. Because of the varied anatomical differences between patients, the RIHM measurements were performed using different measurements angles, resulting in a non-standard measurement between patients, which could possibly influence the reliability. In addition, we were only able to measure 21 hands of a rather heterogeneous group of hypoplastic thumb patients. As a result, there were not enough patients to divide them into more homogeneous patient groups as this would have resulted in groups that were too small for comparison. Furthermore, it should be noted that all measurements were taken after intervention and pre-intervention data were not available.

Overall, we found that with the combined set of strength measurements we were able to draw an appropriate picture of hand strength in a patient group with thumb hypoplasia. While we expected to find a decrease in strength with increasing severity of thumb hypoplasia or radial deficiency, we were surprised by the increase in strength of the abduction of the index or little finger in the most severe cases of thumb hypoplasia. The use of the index finger and the little finger is apparently far more important in these patients. Using the RIHM, we were able to broaden the scope of the strength measurements, illustrating strength patterns on a finger-specific level. Because the RIHM is able to measure specific motor skills of the fingers and thumb, it has added value when evaluating outcome in such patients.

Chapter 7

The added value of measuring thumb and finger strength when comparing strength measurements in hypoplastic thumb patients

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Chapter 8

Discussion

The hand is a complex body part and the function of the hand is determined by, amongst others, muscle strength, coordination, sensibility and range of motion of the joints. Hand function is of major importance for most activities of daily living and impaired hand function may cause limitations in daily life participation. While this thesis focuses specifically on measurements of hand strength, assessing motor and sensory functions is also important. Range of motion plays a role in moving or grasping around different objects and muscle control is needed for good coordination between all different muscles groups involved when performing complex tasks (1-2). In addition, sensory information is vital when touching and handling objects (3). In contrast to the previously mentioned aspects of hand function, our research involved maximum hand strength, which is easily measurable and is often used to assess the overall function of the neuromuscular system. In general, hand strength is part of a larger range of assessment methods to provide outcome in patients groups.

In this thesis, we studied the measurement of hand strength in children. When children with hand disorders receive treatment at a young age, such as in congenital hand disorders, it is important to be able to reliably and validly assess the effect of the treatment on hand strength. Therefore, reliable and valid measurement instruments and appropriate reference values are needed. In addition, not only the generally-used pinch or grip strength may be valuable to measure, but also strength of those fingers or thumb at which the specific intervention is directed. The aim of this thesis was to evaluate the use of hand strength measurements in children and to create reference values for these strength measurements.

Summarizing the main results of the study, it can be concluded that an isometric grip strength dynamometer is preferable over a pressure dynamometer to reliably measure grip strength in children. In addition, we found that the grip strength dynamometer was similarly reliable in children as in adults. Changes to the standard measurement protocol for grip strength measurement, such as providing visual feedback on task performance and reducing the weight of the dynamometer did not significantly improve the reliability. Reference values for the grip strength dynamometer were presented in the form of growth diagrams. These diagrams are easily interpretable and are needed to differentiate between effect of treatment or growth in individual patients. When evaluating the RIHM dynamometer for measuring the strength of the individual fingers or thumb, we found that this instrument is reliable in children from 4-12 years old. Using the same approach for creating and presenting reference values as described above, normative data for the RIHM for children were presented as growth diagrams for thumb strength (thumb palmar abduction, thumb opposition and thumb flexion at the MCP-joint) and for the abduction of the little finger and of the index fingers. Finally, we found that RIHM measurements complement the more commonly-used grip and pinch dynamometers when assessing the hand strength in children with a hypoplastic thumb. Therefore, it can be a valuable addition to assess outcome in patients with congenital hand deformities.

Limitations and strengths of this study

When gathering data to calculate the growth diagrams presented in this thesis, it was not possible to prospectively follow a group of children from early childhood till puberty. Including longitudinal data in statistical growth curve models may allow for more accurate models of the development of individual children than using a transversal data set with one measurement per subject. However, measuring children over longer time periods is very time consuming. Since we used a relatively large group of healthy children and carefully developed growth curves based on non-linear statistically modeling, we feel that our transversal data will be sufficiently accurate to use in clinical practice and in research studies.

For the growth curves of grip strength and RIHM measurements, we included children between 4 -12 years. The age range from 4-12 years includes those children that attend a primary school and as a result children younger than 4 years or children older than 12 years were excluded. For younger children, extending the growth curves may not be possible because children younger than 4 years are generally too immature to be properly instructed and may not be able to concentrate and focus during measurement. For future studies, however, it may be valuable to extend the data pool from 4 years up until adulthood to create continuous reference values.

The current growth diagrams for grip strength and for finger or thumb strength were constructed using a healthy children population in the Netherlands. It should be noted that reference values of healthy children might not always be the best comparison tool for certain patient groups. In our analysis on hand strength measurements in hypoplastic thumb patients we assumed that even though general strength was diminished, patients followed the same, development pattern as in our growth diagrams. In contrast some patient groups might not develop their hand strength analogous to healthy reference values. A comparison, like we performed in the hypoplastic thumb patients, on hand strength can possibly be inaccurate. We can imagine that some patient groups might develop their strength in dissimilar fashion and caution is needed before using healthy reference values as a comparison tool.

One of the strengths of our studies is a more in-depth analysis of the reliability of the strength measurements than most commonly performed in comparable studies. The approach to quantifying reliability in our studies was not solely focused on using Intra Class Correlation Coefficients (ICCs) but also by using the Smallest Detectable Difference (SDD) as an indicator of reliability. The difficulty with ICCs is that they are the ratio of between-groups variance to total variance. Therefore, the ICC is strongly influenced by the variance in the population in which it is assessed. The between-groups variance in a trait-specific-homologous population may be much smaller than in more diverse patient populations. The result is that the ICC in the homologous population is often lower than the ICC from the diverse population and as a consequence ICCs measured for different populations might not be comparable. In contrast, the SDD, which is the amount of change between tests that is needed to detect a real difference in a subject's performance, is a measure of the variance between test and retest without normalization relative to the between-subject variance and expressed in the original unit of measurement such as Newton. It therefore facilitates more direct comparison of reliability between different studies and different populations. Unfortunately, to our knowledge, the SDD is not incorporated in the available software packages such as IBM SPSS statistics. In some situations, SDDs also allow for direct comparison among instruments with different units of measurements by expressing the SDD as a percentage of the outcome of the measurement. Using a combination of ICC's and SDD's to express reliability, we were able to carefully compare reliability of different instruments, different measurement protocols and different age groups (4).

The population sizes used for the reliability studies and for the growth curves can be described as medium-sized, when compared to the literature. For grip strength measurements, we measured 104 children and for RIHM measurements 63. For the reliability, with these sample sizes, we had sufficient power to detect differences between the different instruments (5). Growth curves have been described in literature involving much larger populations (6-

8). Because we used the exact age of each child with their respective strength for calculating our growth diagrams, all individual strength measurements contributed to the single statistical model used to draw the growth diagrams. This approach differs from studies where per one-year or two-year intervals a mean and standard deviation is calculated in a table format (9-10). In the latter case, for each separate age group, sufficient power is needed to obtain a representative sample, while in our case all subjects add to the accuracy of the statistical model.

A final strength in our studies was detected when using RIHM measurements in patients with thumb hypoplasia next to the regular grip and pinch dynamometers. With the RIHM, we were able to measure more detailed aspects of hand strength, For instance the improvement in thumb opposition strength or the loss of small finger abduction by using the abductor of the small finger for thumb opposition. By normalizing our strength measurements in these patients to their age- and gender-specific reference values, we were able to draw a more complete picture on how hand strength was affected throughout the total group of patients than using only grip and pinch strength.

Clinical implications

The findings in this thesis have a number of clinical and practical implications. One such implication is that, based on the findings on reliability of the grip strength and RIHM measurements, these hand strength measurements can already be used in children as young as 4 years, while until today an age of 5 or 6 years was generally considered the minimum (9-10). Since we also provide reference data for children as young as 4 years old, strength data from young patients can be compared to reference values of age-matched controls and by presenting them in the form of growth diagrams the comparison can be done in an intuitive visual manner. Moreover the use of growth diagrams is widely used around the world but had not been previously used for hand strength values. Recently, another research group from the Netherlands presented grip strength growth curves for an 8 to 20 year old population, illustrating the need for such an approach to reference values (8). In addition, since the reliability in children was established for the RIHM, the instrument is used together with regular grip and pinch dynamometers, adding more in-depth detail to the existing hand strength measurements.

Future research suggestions

The present research improves our understanding of a number of aspects related to assessing hand strength in children. However, there are still questions unanswered in this area of research. The scope of our research was on strength measurements in children. The focus on measuring maximum hand strength does not imply that other factors of muscle function are not important. Even though maximum hand strength is easily measureable, it might not be the best indicator of the function of the neuromuscular system of the hand. For instance muscle endurance, muscle fatigue and force control are aspects of neuromuscular function that may not always directly relate to maximum muscle strength but may well be relevant for the patient doing daily life activities. Even though fatigue and control are more difficult to measure their clinical importance is very high. Currently these aspects are difficult to assess but future research might provide better ways for measuring these aspects (8, 11-13). While our focus was only on hand strength, literature suggests varying correlations between hand strength and participation and activity levels. Among others, Jason Shea , Cox et al. suggest statistically significant relations between hand values and dexterity (14-15) while van Meeteren et al. suggest significant relations between hand strength and participation (16). Further research may provide more insight in the relation between hand strength and other muscles strength indicators such as control, fatigue or endurance.

To our surprise, adding visual feedback to the measuring protocol for grip strength did not positively influence reliability of the strength measurements. Despite of this, it was our perception that the use of visual feedback made the measurements more interesting for the subjects, especially for the older children in our population. Therefore, although we did not find any indication that visual feedback facilitated more reliable measurements, it might be worthwhile investigating improvements in providing visual feedback. Updated graphics or special characters (such as from cartoons or television) used in specific games designed to provide better stimuli when performing grip strength measurements, may increase output or reliability.

In the study on thumb hypoplasia patients, we found that the RIHM has added value to the existing grip and pinch measurements. Since the aim of the RIHM is to measure specific aspects of hand function, such as thumb palmar abduction or opposition, we would expect the RIHM to be a more sensitive measure of hand function and therefore be of added value in outcome studies. Preferable, this sensitivity to change would be further evaluated in well-designed outcome studies, such as in a randomized clinical trial (RCT). Unfortunately, RCTs are extremely difficult to perform in congenital hand deformities due to, amongst others, the heterogeneity of the population. Also the long follow-up needed after early-age interventions to assess the results on hand function presents a problem.

Healthy reference values can be used to compare with patients in a particular diagnosis group by expressing strength as a percentage of healthy reference values. This approach gives an indication on how a specific group of patients performs compared to healthy individuals. However the current data we have on all hand strength data is mostly after intervention and is therefore difficult to compare with the situation before intervention. Gathering pre intervention and post intervention data gives better insight in effectiveness of intervention or in hand strength improvements in patients. Children with congenital deformities, however, are often operated under 4 years of age, making it impossible to have hand strength data before intervention. A better approach to validate the use of healthy reference values in certain patient groups may be to directly compare the use of healthy reference values in certain patients groups with group-specific reference values. Comparing healthy reference values with group- specific reference values could clarify if the strength in certain patient groups develops according to the same pattern as in healthy individuals, providing a good argument for using healthy reference values as a comparison tool in the patient groups investigated.

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Chapter 9

Summary

Hand function measurements are often performed to evaluate treatment outcome for interventions aimed at improving hand function. However, hand function is a rather broad term, describing different aspects of the functioning hand and a more systematic approach is needed to describe what aspects one wants to measure. According to the World Health Organization, the systematic description of someone's health condition is comprised of several attributes described in the International Classification of Functioning, Disability and Health (ICF). Besides contextual factors, divided into environmental and personal factors, the three major attributes are Body Function & Structure, Activity and Participation. The focus of this thesis was on hand strength measurements, part of Body Function & Structure, both in healthy children as in children with a congenital hand malformation.

Hand strength can be assessed with instruments that measure different grasping strengths such as tip pinch, key pinch, tripod pinch and grip. For the grip and pinch measurements, we evaluated a number of commonly-used instruments: the Martin Vigorimeter for grip pressure, a grip strength dynamometer similar to the well known Jamar dynamometer, and a pinch dynamometer. These strength measurements are functionally relevant since they measure important daily tasks. However, they have the disadvantage of evaluating a number of different fingers, joints and muscles at the same time. For this reason, we also evaluated the use of the Rotterdam Intrinsic Hand Myometer (RIHM). The RIHM is a device capable of measuring muscle strength of individual fingers and the thumb. With all instruments, we assessed the maximum strength. Maximum strength measurements are relatively easy to perform and such measurements are generally used in medicine to study the function of the neuromuscular system. This thesis focuses on hand strength measurements in children with the aim of further developing tools to assess hand strength in children with different hand pathologies, such as congenital hand deformities. The first aim of this thesis was to establish reliable methods for measuring hand strength in children. The second aim was to generate reference values for these methods. The third aim was to apply the full spectrum of hand and finger strength measurements in a clinical setting and compare the added value of the different instruments.

Chapter 2 compares two grip strength dynamometers commonly used in children. To establish reliability of both instruments, currently unknown in children under 12 years, a test and retest was performed with a mean retest interval time of 29 days. For all measurements, the mean of three maximum voluntary contractions was recorded. A total of 104 children from a primary school were divided into three age groups: 4-6, 7-9 and 10-12 years of age. To compare the instruments on reliability we calculated two parameters: the Intra Class Correlations (ICC) and the Smallest Detectable Difference (SDD). The closer the ICC is to 1 the better the reliability. However, because the ICC is strongly influenced by the variance in the population in which it is assessed, we also calculated the SDD. The SDD is the amount of change between tests that is needed to detect a real difference in a subject's performance and is expressed in the original unit of measurement, such as Newton. The SDD facilitates a more direct comparison of reliability between different studies and different populations, even more so when the SDD is normalized and thus expressed as a percentage of the maximum strength. For the total group, ICCs of the Lode dynamometer were 0.97 for the dominant hand and 0.95 for the non-dominant hand. For the Martin Vigorimeter the ICCs were: 0.84 for the dominant hand and 0.86 for the non-dominant hand. For all separate age groups, ICCs were lower compared to the total group, due to a lower between-subject variation. The normalized smallest detectable difference (SDD) for the Lode dynamometer was approximately 25% and for the Martin Vigorimeter 31%. These results led us to conclude that while both the Lode dynamometer and the Martin Vigorimeter are reliable instruments to measure grip strength in children (<12 years), the Lode dynamometer has higher ICCs, indicating a better test-retest reliability. Moreover, the SDDs also pointed out that the Lode dynamometer is a more reliable instrument.

In chapter 3 we studied if we could improve the reliability of the Lode grip strength dynamometer in children, because this instrument was found to be more reliable than the Martin Vigorimeter. Besides the standard protocol, endorsed by the American Society of Hand Therapists (ASHT), two other protocols were developed. The first protocol used visual feedback by plotting real time on a computer screen the grip force against time. The second protocol reduced the weight of the dynamometer by suspending it. A new group of 63 children from the same preliminary school participated. For the total group, ICCs for the dominant and non-dominant hand were 0.95-0.97 for all protocols, indicating that all three protocols were similarly reliable. This was confirmed by similar SDDs among the three protocols. Therefore, we concluded that the changes in the measurement protocol did not result in a further increase of reliability in this group of healthy children and, as a result, we continued to use the ASHT protocol by default.

In chapter 4 an extra 121 children from the same primary school performed grip strength measurements in order to generate reference values for the ASHT protocol, resulting in grip strength measurements of 225 healthy children in total. Reference values are often presented in a table format with one-year or two-year intervals for each age group. Using normative data in this format can be rather cumbersome when measuring a child over time. For this reason we wanted to develop reference values that would allow for easy distinguishing between normal development in the one hand and intervention effects or disease progression on the other hand. To do so, we first determined which variables in addition to age, such as weight and length, influenced grip strength in our population. Then, we used these variables to develop a statistical model for drawing grip strength growth curves. Overall, grip strength increased with age for both hands. For the whole group the dominant hand produced higher grip strength than the non-dominant hand ($p < 0.001$) and boys were 2%-34% stronger than girls ($p <0.001$) across the different age groups. Separate gender-dependent diagrams were developed, for both dominant hand and non-dominant hand, in addition to a combined model for both genders and hands. Depending on the accuracy needed the use of the combined diagram or the separate diagrams can be considered.

Up till this point the thesis only focuses on grip strength dynamometers, which is an instrument measuring a number of muscle groups in combination and which is dominated by extrinsic hand muscles. In chapter 5 we turned towards the RIHM to measure strength of individual fingers or thumb. To use the RIHM, we first had to establish its reliability in children. In a similar fashion as performed for the grip dynamometer, we performed a test and retest with the RIHM, measuring measure thumb palmar abduction, thumb opposition, thumb flexion in the metacarpophalangeal (MCP) joint, index finger abduction and little finger abduction. The same 63 children as those from the reliability study on the different grip strength protocols participated in this study. Our results, again expressed in ICCs and SDDs, were as follows: For the thumb, palmar abduction strength had an ICC of 0.98 for both hands. For thumb opposition and flexion in MCP, ICCs were 0.97 and 0.98 for the dominant and non-dominant hand. Index finger abduction had ICCs of 0.94 and 0.95 and little finger abduction 0.90 and 0.92. The normalized SDD for dominant and non dominant hand were for thumb palmar abduction 15% and 15%, for thumb opposition 12% and 9%, for thumb flexion (at MCP level) 12% and 9%, for abduction of the index finger 17% and 17%, and for little finger abduction 26% and 26%. These values were comparable to those of the RIHM in adults as well as to values found for pinch and grip strength in children. Because of the good reliability and because the RIHM is capable of measuring different aspects of a child's hand strength, we conclude that children as young as 4 years can be reliably measured with the RIHM.

Chapter 6 of this thesis focuses on establishing reference values on the RIHM in children. For the same reasons as when developing growth diagrams for grip strength, we developed growth diagrams for the RIHM as an alternative to a table format. A total of 101 children from the same primary school participated for the following RIHM measurements: thumb palmar abduction, thumb opposition and thumb flexion in the metacarpal phalangeal joint as well as abduction of the index- and little finger. Additionally, we determined hand-dominance, age, gender, height, and weight to calculate the best model for drawing the growth diagrams. Separate models for dominant and non-dominant hand of boys and girls were developed as well as a combined model. Because there was no significant difference in strength between boys and girls and between dominant and non dominant hand, we combined them for each growth diagram. A total of five growth diagrams for the RIHM were developed, allowing tracking of multiple strength measurements of a growing child over time.

Chapter 7 focuses on hand strength measurements in patients with thumb hypoplasia. The aim was to evaluate and compare the spectrum of different strength measurements in these patients: a pinch dynamometer, a grip dynamometer and the RIHM. More specifically, the aim was to determine if the RIHM would be able to assess different aspects of hand strength compared to pinch and grip strength in this group of hypoplastic thumb patients. 40 patients diagnosed with thumb hypoplasia were included in this study with 65 affected hands. Thumb hypoplasia was scored using the Blauth classification and radial longitudinal deficiency was classified into either mild or severe radial longitudinal deficiency. In these patients, 21 "Flexor Digitorum Superficialis of the fourth finger" (FDS4) tendon transfers for opposition and MCP joint instability were performed, with or without 1st web deepening, 16 abductor digiti quinti transfers for opposition and 28 pollicisations. Besides grip, tip pinch, tripod pinch and key pinch strength, we used the Rotterdam Intrinsic Hand Myometer to measure thumb palmar abduction and thumb opposition strength. In addition, we measured abduction of the index finger and little finger. For the mild and severe radial longitudinal deficiency patients, combined grip and pinch strength as well as palmar abduction and thumb opposition were significantly lower than references values. However, strength in the index finger abduction and the little finger abduction was not decreased, possibly due to compensation because of the failing function or absence of the thumb. Blauth type II hands that received a FDS4 to improve opposition and MCP joint stability, compared to non-operated Blauth type II hands, showed a significant lower grip strength but the same group showed a trend towards a higher opposition strength (p=0.094). Overall, the combined set of strength measurements was able to draw an appropriate picture of hand strength in a patient group with thumb hypoplasia. Using the RIHM, we were able to illustrate strength patterns on a finger-specific level, showing the added value of the RIHM when evaluating outcome in patients with hand related problems.

Chapter 8 discusses the overall outline of this thesis in a broader perspective. As some of the limitations of this study, we describe the limitation of the age range from 4 to 12 years, while the strengths of our studies include the more in-depth analysis of the reliability of the strength measurements than most commonly performed in comparable studies, the sufficient power we had with respect to population size to detect differences in reliability between the different instruments, the presentation of the normative data using growth curves, and the introduction of the RIHM to measure more detailed aspects of hand strength in healthy children and in children with congenital hand deformities. We also discuss a number of clinical and practical implications. One such implication is that, based on the findings on reliability of the grip strength and RIHM measurements, these hand strength measurements can already be used in children as young as 4 years and compared to the proper age-matched reference values in the form of growth curves. For future research it may be interesting to look into other clinical important aspects of the neuromuscular system of the hand, such as muscle endurance, muscle fatigue and force control. In addition a further evaluation of the RIHM in well-designed outcome studies, such as in a randomized clinical trial (RCT) would be appropriate. Finally a better approach to validate the use of healthy reference values in certain patient groups may be to directly compare healthy reference values in certain patients groups with group-specific reference values in order to investigate if strength in some patient groups develops according to the same pattern as it does in healthy individuals.

Chapter 10

Samenvatting -

Het meten van handkracht bij kinderen

Handfunctie metingen worden vaak gebruikt om de uitkomst te evalueren van behandelingen gericht op het verbeteren van de hand functie. Aangezien handfunctie een vrij brede term is, is het beter om verschillende functie aspecten van de hand systematischer te beschrijven. De “World Health Organization” beschrijft gezondheid volgens de “International Classification of Function, Disability and Health” (ICF). Dit model bestaat naast omgevings- en persoonlijke factoren uit Lichaam Functie & Structuur, Activiteit en Deelname. Dit proefschrift richt zich op handkrachtmetingen (als onderdeel van Lichaam Functie & Structuur) bij gezonde kinderen maar ook bij kinderen met aangeboren hand afwijkingen.

Het meten van handkracht gebeurt gewoonlijk met instrumenten gericht op het meten van verschillende knijp- en grijp functies van de hand, zoals pincetgreep, sleutelgreep, 3-vingertoppengreep en grijpkracht. Voor grijp- en knijpkracht onderzochten we een aantal veelgebruikte meetinstrumenten: de Martin Vigorimeter die grijpdruk meet, een grijpkracht dynamometer lijkend op de Jamar dynamometer en een knijpkracht dynamometer voor het meten van pincet- sleutel- of 3-vingergreep. Deze metingen zijn zeer relevant aangezien deze functies veel gebruikt worden in het dagelijks leven. Daarentegen hebben deze instrument een nadeel omdat ze altijd meerdere vingers, gewrichten en spieren tegelijk meten. Om die reden onderzochten we ook de Rotterdamse Intrinsiek Hand Myometer (RIHM), een instrument dat de kracht van individuele vingers of de kracht van de duim kan meten. Elk van de bovengenoemde instrumenten werd gebruikt voor het meten van maximale kracht, aangezien het meten van maximale kracht vrij makkelijk uit te voeren is en maximale kracht metingen in de gezondheidszorg vaak gebruikt worden om de algehele conditie van zenuwen en spieren te meten.

De focus van dit proefschrift lag op handkrachtmetingen bij kinderen met als doel het ontwikkelen van middelen om handkracht te evalueren bij kinderen met verschillende handaandoeningen, zoals bijvoorbeeld aangeboren handafwijkingen. Het eerste doel van dit proefschrift was om betrouwbare methoden voor het meten van handkracht bij kinderen te creëren. Het tweede doel bestond uit het ontwikkelen van goede referentiewaarden voor deze methoden. Het derde doel bestond uit het toepassen van alle hand- en vingerkrachtmetingen in een klinische situatie, waarbij de meerwaarde van ieder instrument werd vergeleken.

Hoofdstuk 2 vergelijkt twee bekende grijpkracht dynamometers voor gebruik bij kinderen. De betrouwbaarheid van beide instrumenten was tot op heden onbekend voor kinderen jonger dan twaalf jaar. Om de betrouwbaarheid in kaart te brengen werd een test-hertest uitgevoerd met een gemiddeld interval van 29 dagen. Alle metingen bestonden uit het gemiddelde van drie maximaal vrijwillige krachtsinspanningen. 104 kinderen van een basisschool werden verdeeld in drie leeftijdsgroepen: 4-6, 7-9 and 10-12 jaar. Om de betrouwbaarheid tussen beide instrumenten te vergelijken berekende we twee parameters: de Intra Class Correlatie (ICC) en de Smallest Detectable Difference (SDD). Hoe dichter de ICC bij 1 komt des te beter is de betrouwbaarheid. Maar aangezien een ICC sterk beïnvloed wordt door de variantie van de betreffende populatie, wendden we ons daarnaast tot het gebruik van de SDD. De SDD, uit te drukken in dezelfde eenheid van het betreffende meetinstrument (bv. Newton), is het minimale verschil tussen twee metingen dat nodig is om daadwerkelijk verschil in uitkomst te kunnen detecteren. Met behulp van de SDD is het mogelijk om betrouwbaarheid tussen verschillende instrumenten of studies te vergelijken. Voor de totale groep kinderen was de ICC van de Lode dynamometer 0.97 voor de dominante hand en 0.95 voor die niet-dominante hand. Voor de Martin Vigorimeter was de ICC 0.84 voor de dominante hand en 0.86 voor die niet-dominante hand. Bij alle leeftijdsgroepen waren de ICCs lager dan voor de totale groep, waarschijnlijk als gevolg van een lager intra-proefpersoon variatie. De genormaliseerde SDD, uitgedrukt in een percentage van de maximale kracht, was voor de Lode dynamometer ongeveer 25% en voor de Martin Vigorimeter 31%. Hieruit concludeerden we dat beide meetinstrumenten betrouwbaar zijn voor het meten van grijpkracht bij kinderen tot 12 jaar oud. De Lode dynamometer was betrouwbaarder mede dankzij de hogere ICCs. Daarnaast lieten de SDDs ook zien dat de Lode dynamometer een meer betrouwbaar instrument is.

In hoofdstuk 3 onderzochten we of het mogelijk was om de betrouwbaarheid van de Lode grijpkracht dynamometer te verbeteren bij kinderen. Om dat te bewerkstelligen ontwikkelde we naast het standaard protocol van de “American Society of Hand Therapists” (ASHT), ook twee andere protocollen. Het eerste protocol gebruikte visuele terugkoppeling door direct op een computerscherm de uitgeoefende kracht tegen de tijd weer te geven. Het tweede protocol gebruikte een ophangsysteem voor de dynamometer waardoor het gewicht van het instrument verwaarloosbaar werd. Een nieuwe groep van 63 kinderen van dezelfde basisschool namen deel in dit onderzoek Voor de totale groep waren de ICCs voor de dominante-en niet-dominante hand 0.95-0.97 voor ieder protocol, aangevend dat er geen verschil in betrouwbaarheid was. Deze conclusie werd verder onderbouwd door dezelfde SDD waarden van ieder protocol. Concluderend vonden we dat een verandering in meetprotocol leidt niet tot een meer betrouwbare meting bij gezonde kinderen, met als resultaat dat de Lode dynamometer in gebruik kan blijven volgens het ASHT protocol.

Hoofdstuk 4 had tot doel normaalwaarden te generen voor de Lode dynamometer bij gebruik volgens het ASHT protocol. Nog eens 121 kinderen van dezelfde basisschool werden gemeten met de grijpkracht dynamometer, wat leidde tot een totale groep van 225 kinderen. Normaalwaarden worden vaak gepresenteerd in een tabelvorm met 1-jaars- of 2-jaars intervallen voor iedere leeftijdsgroep. Het lezen en interpreteren van een dergelijke tabel is vaak lastig wanneer een kind meerdere keren gemeten wordt over een langere periode. Om dit probleem te ondervangen, wilden we normaalwaarden genereren waarmee op eenvoudige wijze het onderscheid is te maken tussen normale groei van een kind en diens kracht toename als gevolg van interventie of ziekte progressie. Als eerste hebben we bepaald welke verschillende variabelen zoals leeftijd, gewicht, lengte en geslacht van invloed zijn op de grijpkracht. Vervolgens zijn deze variabelen gebruikt om door middel van een zo goed mogelijk statistisch model groeidiagrammen voor grijpkracht te ontwikkelen. Gemiddeld nam de kracht toe met de leeftijd. Voor de hele groep was de kracht in de dominante hand groter dan the kracht in de niet-dominante hand and de jongens waren sterker dan de meisjes. Voor ieder geslacht en voor zowel de dominante- als de niet-dominante hand werden aparte groeidiagrammen ontwikkeld. Daarnaast werd ook één groeidiagram ontwikkeld voor beide geslachten en handen. Afhankelijk van hoe nauwkeurig het groeidiagram moet zijn kan men besluiten om een gecombineerd diagram te gebruiken of de afzonderlijke diagrammen.

To zover lag de focus in dit proefschrift op grijpkracht dynamometers, welke altijd een aantal spiergroepen in combinatie meten en waarbij hoofdzakelijk de extrinsieke handspieren een rol spelen. In hoofdstuk 5 hebben we de RIHM gebruikt voor het meten van individuele vingerkracht of duimkracht. Om de RIHM te gaan gebruiken bij kinderen moest ook hier eerst de betrouwbaarheid in kaart worden gebracht. De methodiek was gelijk aan die gebruikt bij de grijpkracht dynamometers. Een test en hertest werden uitgevoerd met RIHM-metingen van de palmair abductie van de duim, de duimoppositie en duimflexie in het metacarpophalangeaal (MCP) gewricht, van de wijsvinger abductie en van de pink abductie. Dezelfde groep van 63 kinderen van het onderzoek naar de betrouwbaarheid van de verschillende grijpkracht protocollen nam deel aan deze studie. Uitgedrukt in ICCs en SDDs waren onze resultaten als volgt: voor de palmair abductie van de duim was de ICC voor beide handen 0.98. Voor duimoppositie en duimflexie ter hoogte van het MCP gewricht waren de ICCs 0.97 en 0.98 voor respectievelijk de dominante en de niet dominante hand. Voor abductie van de wijsvinger waren de ICCs 0.94 and 0.95 en voor de pink abductie 0.90 en 0.92 voor de dominante en niet-dominante hand. De genormaliseerde SDDs voor de dominante en de niet dominante hand voor palmair abductie van de duim waren 15% en 15%. Oppositie van de duim had genormaliseerde SDDs van 12% en 9% en bij duimflexie ter hoogte van MCP waren de genormaliseerde SDDs 12% en 9%. De genormaliseerde SDD voor zowel de dominante hand als de niet dominante hand bij abductie van de wijsvinger was 17% en bij abductie van de pink was deze 26%. De gevonden waarden waren vergelijkbaar met literatuurwaarden van volwassenen gevonden bij de RIHM en knijp- en grijpkracht dynamometers en we concluderen dan ook dat kinderen vanaf 4 jaar reeds betrouwbaar gemeten kunnen worden.

In hoofdstuk 6 van dit proefschrift ligt de focus op het in kaart brengen van goede normaalwaarden van de RIHM bij kinderen. Ook voor de RIHM werd de zelfde aanpak van groeidiagrammen gebruikt bij het maken van de normaalwaarden. 101 kinderen van dezelfde basisschool namen deel aan dit onderzoek en bij hen werden metingen verricht van de palmair abductie van de duim, duimoppositie en duimflexie in het metacarpophalangeaal (MCP) gewricht, wijsvinger abductie en pink abductie. Om een goed model voor de groeidiagrammen te berekenen zijn ook leeftijd, handdominantie, geslacht, lengte en gewicht gemeten. Dit resulteerde in vijf verschillende modellen per RIHM meting: Voor de dominante hand of niet dominante hand en voor jongens of meisjes apart, maar ook een gecombineerd model omdat er er geen significant verschil tussen beide handen of tussen jongens en meisjes werd gevonden.

Hoofsttuk 7 had tot doel om alle verschillende handkrachtmetingen te evalueren en onderling te vergelijken in een patiëntengroep met duim hypoplasie (een aangeboren mindere aanleg van de duim). Meer specifiek was het doel om in deze patiëntengroep te bepalen of de RIHM in staat was om aanvullende aspecten van de handkracht te meten in vergelijking tot grijp- en pincetkracht. 40 patiënten met 65 aangedane handen gediagnosticeerd met duim hypoplasie werden geïncludeerd in deze studie. Duim hypoplasie werd geclassificeerd volgens Blauth en longitudinale radius deficiëntie werd gecategoriseerd in milde of ernstig longitudinale radius dysplasie. Van deze patiënten hadden 21 handen een "Flexor Digitorum Superficialis van de vierde vinger" (FDS4) peestranspositie ondergaan om oppositie en MCP gewrichtsstabiliteit te verbeteren, met of zonder verdieping van de eerste interdigitaal plooi, 16 handen ontvingen een abductor digiti quinti transfer ter verbetering van de duim oppositie en 28 pollicisaties waren uitgevoerd, dat wil zeggen het maken van een duim van de wijsvinger. Naast het meten van grijp- en pinceptkracht werd de RIHM gebruikt voor het meten van palmair abductie van de duim, duimoppositie en duimflexie in het metacarpophalangeaal (MCP) gewricht, wijsvingerabductie en pinkabductie. Voor de totale groep met longitudinale radius deficiëntie was de grijp- en pinceptkracht, maar ook de palmair abductie en oppositie van de duim significant lager dan de bestaande normaalwaarden. Daarentegen was de abductie van de wijsvinger en de abductie van de pink niet afgenomen, mogelijk als compensatie voor de verminderde functie of afwezigheid van de duim. Hoewel Blauth type II handen die een FDS4 transpositie ontvingen een significant lagere grijpkracht hadden vergeleken met niet-geopereerde Blauth type II handen, was er een trend (p=0.094) waarneembaar richting meer oppositie kracht in de groep met FDS4 transposities. Gemiddeld genomen was het mogelijk om door middel van alle krachtmetingen een duidelijk beeld te scheppen van de handkracht in patiënten met duim hypoplasie. Middels de RIHM was het mogelijk om op vingerniveau kracht in kaart te brengen, wat duidelijk de meerwaarde van het gebruik van de RIHM aantoont bij patiënten met handproblemen.

Afsluitend plaatst hoofdstuk 8 dit proefschrift in een breder perspectief. Een beperking van ons onderzoek is onder ander de leeftijdsinterval van 4 tot 12 jaar. Echter ons onderzoek voegt ook veel waarde toe door de meer gedetailleerde aanpak bij het meten van betrouwbaarheid van krachtmetingen dan in vergelijkbare studies gebruikelijk. Daarnaast was onze populatie was groot genoeg om verschillen in betrouwbaarheid tussen de meerdere meetinstrumenten vast te stellen. Een verdere kracht van onze studie is het modelleren van groeidiagrammen om de gevonden normaalwaarden weer te geven en het gebruik van de RIHM om meer gedetailleerde aspecten van handkracht te kunnen meten in gezonde kinderen en kinderen met aangeboren handafwijkingen. We bespreken ook een aantal klinische en praktische implicaties. Een van deze implicaties, gebaseerd op onze gemeten betrouwbaarheid bij grijpkrachtmetingen en RIHM metingen, is dat al deze metingen reeds bij kinderen vanaf 4-jarige leeftijd gebruikt kunnen worden. Daarnaast is het nu mogelijk om deze metingen te vergelijken met leeftijdsgerelateerde normaalwaarden. Voor de toekomst kan het interessant zijn dieper in te gaan op andere klinisch belangrijke aspecten van het neuromusculaire systeem van de hand, zoals spieruithoudingsvermogen, spiervermoeidheid en krachtscontrole. Tevens is het aan te raden om de RIHM verder te onderzoeken middels een goed ontworpen studie, zoals bij een "randomized clinical trial (RCT)". Tenslotte zou het goed zijn om het gebruik van gezonde normaalwaarden te valideren in patiëntengroep door de normaalwaarden te vergelijken met groep-specifieke waarden om zo te onderzoeken of handkracht in de patiëntengroepen zich ontwikkeld volgens het zelfde patroon van de gezonde normaalwaarden.

Chapter 11

Curriculum Vitae

Dankwoord

Curriculum Vitae

Ties Molenaar was born on March 19th 1975 in Leiden, the Netherlands. After his graduation in 1994 from the Stedelijk Gymnasium in Leiden, Ties chose to move to Delft to study System Engineering, Policy Analysis & Management. Eventhough the technical side was appealing, he leaned more towards healthcare. Because of the numerous fixus for a study in medicine, Ties first studied Biology in 1997. Finally in 1998, he was able to study medicine at the University of Leiden. During his study on medicine he was employed at a logistics company at Schiphol airport. After finishing the graduation research for his master of science in medicine 2006, he started his PhD study on “Measuring Hand Strength in Children” at the department of Plastic, Reconstructive and Hand Surgery at the Erasmus MC in Rotterdam. During his PhD he succesfully completed his Executive Master in Business Administration at the Rotterdam School of Management (2009) in order to bridge the gap between healthcare and a business environment. In the future Ties hopes to effectively combine his knowlegdge in medicine and in business administration.

Dankwoord

Wat ik ooit niet voor mogelijk achtte is toch realiteit geworden: mijn boekje is af. Wat begon als een onderzoek met onzekere uitkomst, kwam al snel tot leven toen ik mijn gegevens ging verzamelen en daarop ging analyseren. Gegevens kregen een betekenis en leidde tot goede resultaten. Allereerst mijn dank aan allen die hebben bijgedragen aan dit proefschrift. Een aantal personen wil ik graag nog in het bijzonder bedanken:

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