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LONG-TERM OUTCOME OF MUSCLE STRENGTH IN ULNAR AND MEDIAN NERVE INJURY: COMPARING MANUAL MUSCLE STRENGTH TESTING, GRIP AND PINCH STRENGTH DYNAMOMETERS AND A NEW INTRINSIC MUSCLE STRENGTH DYNAMOMETER

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Objective: **To compare the outcome of muscle strength with manual muscle strength testing grip and pinch strength measurements and a dynamometer which allows for measurements of the intrinsic muscles of the hand in isolation (the Rotterdam Intrinsic Hand Myometer, RIHM).**
Methods: **Thirty-four patients more than 2 years after ulnar and/or median nerve injury. Muscle strength was evaluated using manual muscle strength testing (MMST), grip, pinch and intrinsic muscle strength measurements.**
Results: **Manual muscle strength testing showed that most muscles recover to grade 3 or 4. Average grip strength recovery, as percentage of the uninjured hand, was 83%. Pinch strength recovery was 75%, 58% and 39% in patients with ulnar, median and combined nerve injuries, respectively. The RIHM measurements revealed a poor recovery of the ulnar nerve innervated muscles in particular (26–37%). No significant correlation (Pearson) was found between the measurements of the RIHM and grip strength. Pinch strength was significantly correlated with strength of the abduction of thumb and opposition of the thumb strength (r 0.55 and 0.72, p = 0.026, 0.002) as measured with the RIHM.**
Conclusion: **While manual muscle strength testing and grip strength measurements show a reasonable to good recovery, measurements of the intrinsic muscles by means of the RIHM showed poor recovery of intrinsic muscle strength after peripheral nerve injury. No correlation was found between the recovery of intrinsic muscle strength and grip strength measurements.**

Key words: outcome assessment, hand injuries, ulnar nerve, median nerve, hand strength.

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INTRODUCTION

Peripheral nerve lesions constitute a major reason for severe and longstanding impairment in hand function (1). Outcome is often unpredictable and disappointing with poor recovery of sensibility, loss of motor function, cold intolerance and pain, leading to loss of function, limitations in activities and social participation (2), and can cause considerable psychological stress (3). The most frequently used method to evaluate the outcome of motor function is the manual muscle strength testing (MMST) introduced by the British Medical Research Council (MRC) 0–5 scale (4). In addition to MMST, grip and pinch strength measurements with dynamometers are increasingly becoming a standard for evaluation of the outcome of peripheral nerve function (5–9). There are, however, reasons to question the appropriateness of the present methods in evaluating the recovery of muscle strength after peripheral nerve injuries. Firstly, measuring the recovery with the MMST using the ordinal MRC scale provides too little differentiation in the 4–5 segment of the scale (10). Secondly, grip and pinch strength measurements provide information on the strength of the combined action of all the muscles of the forearm and hand, and not exclusively of the median or ulnar nerve innervated intrinsic muscles. Thirdly, traumas of the forearm usually involve injuries of associated tissues, e.g. flexor tendons, which will have a negative effect on the grip strength (11–13).

To avoid the aforementioned difficulties, quantitative measurements that can specifically measure the intrinsic muscle strength are required. Such instruments have been developed, e.g. to measure the abduction strength of the thumb (14–17) or the Mannerfelt intrins-o-meter to measure the abduction strength of the little finger and the index finger (18). The Rotterdam Intrinsic Hand Myometer (RIHM) (Fig. 1) is a new dynamometer which enables measurement of 2 intrinsic muscle movements for the ulnar nerve innervated movements; i.e. abduction of the index and little fingers, and 2 for the median nerve innervated intrinsic muscles of the thumb; i.e. palmar abduction and opposition of the thumb. Reliability and measurement error in patients with peripheral nerve injuries are reported to be acceptable (19).

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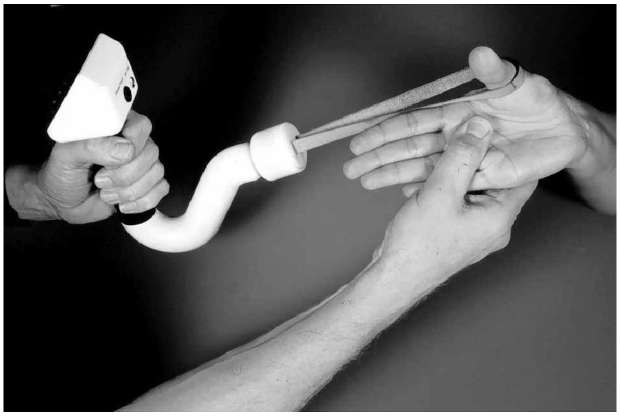

Fig. 1. Intrinsic measurement of the strength of the abduction of the thumb with the Rotterdam Intrinsic Hand Myometer (RIHM).

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

MATERIAL AND METHODS

We requested patients who had suffered a unilateral traumatic median, ulnar, or combined median ulnar nerve injury, which were primarily repaired by surgeons specialized in hand surgery, to participate in this study. Thirty-four patients (28 men and 6 women) with a mean age of 36 years (range 16–70 years; SD 12.7), who had suffered an injury more than 2 years previously, were included. The average time between the assessment and the injury was 7.3 years (range 2.1–32.2 years; SD 6.4). Of the 34 patients 27 patients (79%) sustained an injury to 1 or more tendons and major blood vessels, 6 patients (18%) to 1 or more muscle bellies and 2 patients had a fracture. Only 4 out of the 34 patients had an isolated nerve injury. In 42% the left hand, and in 58% the right hand was injured, respectively. In 65% the dominant hand was injured including the 2 left-hand dominant patients.

Patients were divided into 3 groups; ulnar nerve injury (14 patients), median nerve (12 patients) and combined ulnar and median nerve injury (8 patients). All injuries were in the forearm located between the elbow and the wrist.

Patients had attended the rehabilitation department and were treated according to a standard hand therapy protocol (20). The sutured nerve was protected for 3–4 weeks with a splint to prevent tension on the nerve. The 4–6 weeks following this first phase patients visited the rehabilitation department 1–2 times a week for exercises to regain full mobility. Patients were taught exercises to prevent contractures and wounds to the insensate parts of their hand. Following this period patients were usually attending the rehabilitation department once a month when routine nerve assessments were done.

Four methods of measuring the muscle strength of the hand were studied. Firstly, intrinsic muscle strength was assessed by use of MMST according to Brandsma et al. (21). Four movements were measured; the abduction of little and index fingers for the ulnar nerve, and abduction and opposition of the thumb for the median nerve. In addition, we examined whether patients were able to adduct the little finger and move the middle finger sideways. An inability to adduct the little finger is called the Wartenberg sign (22) and the inability to ab- and adduct the middle finger is the Egawa sign (23), both signs of ulnar nerve muscle weakness.

Secondly, grip and pinch strength measurements were performed with the Lode “hand grip” and “pinch grip” dynamometers, (produced and distributed by Lode Medical Technology, Zernikepark 16, 9747 AN Groningen, The Netherlands) which are similar to the Jamar and Preston dynamometers. For the grip strength measurements the second handle position was used (distance between the handles of 4.6 cm) and for the pinch strength measurements the “tip-to-tip” pinch was done between the tip of the index finger and thumb, with the other fingers flexed. According to the recommendations of the American Society of Hand therapists (ASHT) (24) participants were comfortably seated at a table on which the dynamometers were positioned. The subjects were told to keep their shoulders adducted and their elbow flexed without resting their arm or the grip handle of the dynamometer on the table. After an explanation of the tasks, the examiner told each subject, “Squeeze the dynamometer as hard as you can” and “Go”. No feedback regarding the performance was given during the measurement. Measurements were obtained of the left and right hands alternately, and for each measurement, the mean of 3 repetitions was recorded.

Finally, the RIHM was used to measure the strength of the intrinsic muscles of the hand. As with MMST, the same 4 movements were tested and were performed with a comparable procedure concerning, for example, the hand position, position of applying pressure, and instructions.

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

For the ulnar nerve innervated muscles, 2 measurements were carried out:

- Ulnar abduction of the little finger. The patient’s hand was in supination while the second, third and fourth fingers were held by the examiner’s hand. The patient’s little finger was placed in maximum abducted position with the metacarpal phalangeal (MP) joint in slight flexion. The patient was told to keep the finger in that position while the sling of the dynamometer was applied at the proximal interphalangeal (PIP) joint of the little finger. The pull was always perpendicular to the little finger in a straight line with the palm of the hand.
- Radial abduction of the index finger (mainly the first dorsal interosseus muscle). The patient’s hand was in pronation and the third, fourth and fifth fingers were held by the examiner. The point at which the sling was applied was at the radial side of the PIP joint of the index finger. The pull was always perpendicular to the finger; parallel to the palm of the hand.

For the median nerve innervated muscles, 2 measurements were carried out:

- Palmar abduction of the thumb. The lower arm was in supination with the elbow resting on the table with the wrist manually supported by the examiner in dorsiflexion. The sling was applied at the MP joint level of the thumb. The patient was asked to move the thumb away from the palm of the hand. The strength was in one line with the flexion-extension axis of the MP joint of the thumb (Fig. 1).
- Opposition of the thumb. The lower arm was supinated and all fingers of the hand were fixed flat on the table by the examiner. The pull was at the MP joint in a horizontal plane in line with the palm of the hand. The patient was instructed not to flex the interphalangeal joint of the thumb.

Measurement results were expressed as the “percentage recovery” of the uninjured hands. Evaluating motor function recovery as a quantitative percentage of the uninjured side provides a useful method of normalizing the results to compensate for the variability of patient strength (16). Of the measurements with the dynamometers the mean and SD were calculated. In 10 measurements of 6 patients muscle strength was less than grade 3 (Table I). In these cases RIHM dynamometry was not possible because no resistance could be given and in these cases a “0” score was recorded.

For abduction of the little and index finger, the relation between the 4 different methods of muscle strength testing was assessed in patients with a single ulnar nerve injury and in those with combined ulnar and median nerve injuries ($n = 24$). In the same way, for both thumb

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

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

movements, 1 group was formed of patients with median nerve and combined injuries (*n* = 20).

The relation between the MMST and RIHM dynamometry muscle strength testing was assessed by calculating the Spearman correlation coefficient. The Pearson correlation coefficient was calculated between the percentage recovery as measured with the 3 dynamometers for grip strength, pinch strength and intrinsic muscle strength (RIHM).

RESULTS

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

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

Table II presents the outcome of the muscle strength, expressed as "percentage recovery" of the uninjured hand, of grip and pinch strength measurements and the RIHM measurements of the four movements. The average outcome of grip strength in the three groups of patients was comparable; i.e. 77 to 88%. Loss of pinch strength is greatest in patients with the combined nerve injuries, and is greater in patients with a median nerve injury than in patients with an ulnar nerve injury. The abduction of the index finger strength as measured with the RIHM in 14 ulnar nerve injured hands is remarkably low; only 26% of the uninjured side. The abduction of the thumb strength in patients with single median nerve and combined nerve injuries was 59% and 27% of the uninjured hand, respectively. Figure 4 presents the average percentage recovery

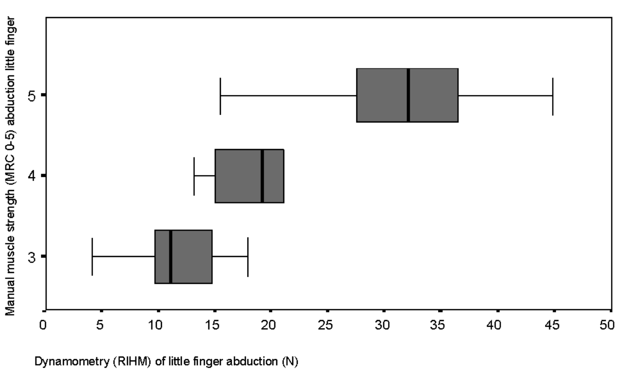

Fig. 2. Strength of the abduction of the little finger: assessed by means of MRC grade 3, 4 and 5 and measured with the RIHM dynamometer (N). The box represents the interquartile range, which contains the 50% of values. The whiskers are lines that extend from the box to the highest and lowest values and the line across the box indicates the median. The MRC grade 5 refers to the uninvolved hands of the 34 patients.

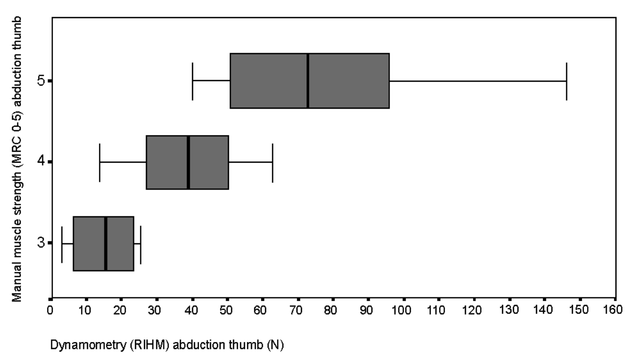

Fig. 3. Strength of the abduction of the thumb: assessed by means of MRC grade 3, 4 and 5 and measured with the RIHM dynamometer (N). The box represents the interquartile range, which contains the 50% of values. The whiskers are lines that extend from the box to the highest and lowest values. The line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

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

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

RIHM = Rotterdam Intrinsic Hand Myometer.

of the intrinsic muscles compared with grip and pinch strength measurements for the 3 groups of patients.

There was a significant relation found between MMST and the RIHM dynamometry measurements of all 4 movements (Table III); Spearman correlation coefficients were 0.65, 0.63, 0.85 and 0.56 for little finger, index and thumb abduction and opposition of thumb, respectively (p-values from 0.001 to 0.014). No significant correlation was found between the four measurements of the RIHM and the grip strength measurements. Pinch strength was significantly correlated only with strength of the abduction of thumb and opposition of the thumb strength (Pearson r; 0.55 and 0.72, $p = 0.026$, 0.002) as measured with the RIHM. Pinch strength was not correlated with grip strength measurements.

DISCUSSION

The evaluation of muscle strength is, in combination with the assessment of sensibility, an important clinical method to determine ulnar and median nerve function. This information is valuable in decision-making concerning surgery (e.g. tendon transfers), therapy (e.g. splints), advice in work-related issues (e.g. safety to work with machines) and research issues (e.g. nerve repair technique). Concerning this latter topic, Trumble et al. (16) noted that without extremely sensitive methods for monitoring the functional outcome of nerve regeneration, it will be difficult to identify those factors that may have small but additive beneficial effects and those that may have negative effects on nerve regeneration.

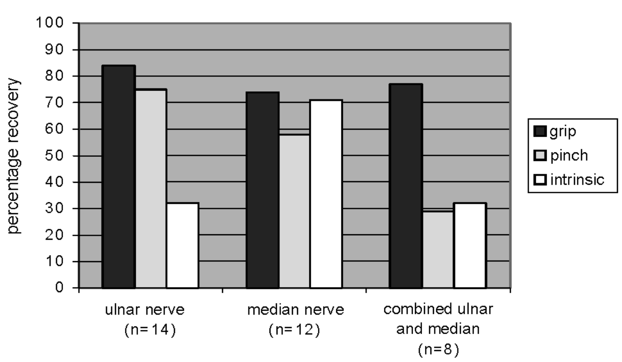

Fig. 4. Average percentage recovery of grip, pinch and intrinsic muscle strength of 3 groups of patients; ulnar nerve, median nerve and combined nerve injury.

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

Besides the problem with grading, there is disagreement as to what constitutes a functional level of muscle strength recovery after peripheral nerve injury using grades 0–5. In literature, useful or functional motor recovery has been defined anywhere from 2+ level of recovery to a 4–5 level (22). Seddon (25) defined a "good" motor outcome as grade 3 or better and reported that 47.6% of his patients with nerve injuries obtained this level. Frykman (26) reached a higher percentage of grade 3 or better; 81% and 64% after median and ulnar nerve injuries, respectively. Strickland et al. (22) selected grade 4 for determining a good result, which was obtained in 9 of 17 patients with ulnar nerve injuries. In the patients in the present study, very few measurements of the intrinsic muscles (9/84) reached grade 5. Of all the 84 MMST measurements 75% were grade 3 and 4.

Although it is imperative to come to an agreement as to what should be considered as a good motor outcome on the MRC scale, the more important question is whether this method is sensitive enough to sufficiently differentiate above the grade 3 level. We consider MMST to be an important and useful method in the 0–3 grades of the MRC scale, but for strength measurements above grade 3 a more accurate evaluation method is required. Grip and pinch strength dynamometry is a more sensitive method to determine muscle strength and to render outcome on a continuous scale, e.g. kilogram force or Newton. These quantitative outcomes, which

Table III. *Correlation between different muscle strength testing methods*

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

RIHM = Rotterdam Intrinsic Hand Myometer.
[a] Spearman correlation coefficient, [b] Pearson correlation coefficient.
* $p < 0.05$, n.s. = not significant.

will also facilitate statistical analyses, have been proposed as a standardized method to evaluate motor recovery in patients with peripheral nerve injuries (5, 7, 8). Reliable application of these measurements requires little training and is not influenced by the experience of the examiner (27). Another benefit is that evaluating motor function recovery as a percentage of the uninjured side is possible using the uninvolved hands as the normal level of strength for that patient. Therefore the data can be normalized and allows to compensate for the large variability in patient strength.

In our study the mean recovery of grip strength, compared with the uninjured hand, was 84% in the 14 patients with an ulnar nerve injury. Rosén (7) and Strickland et al. (22) found comparable grip strength recoveries of 88% and 89.9%, respectively. Commenting on these grip strength results, Strickland et al. (22) made a noteworthy remark that grip and pinch strength may only be used as an indirect measurement of ulnar nerve outcome. Although grip strength measurements do fulfil the requirements for quantitative outcome of the strength of the hand, they cannot differentiate between the intrinsic and extrinsic muscles. Strong grip strength does not necessarily coincide with strong intrinsic muscles. The results of the present study give more specific insight in the recovery of the intrinsic muscle strength.

It remains debatable what the precise contribution of the intrinsic muscles are in grip and pinch strength measurements (28, 29). It has been suggested that the most narrow handle position (position 1) of the Jamar dynamometer could be used to test the strength of the intrinsic muscles, whereas the wider handle (position 4 and 5) could be used to test the extrinsic finger flexors (30). In another study EMG recordings of hand muscles in sustained grasp in the different handle positions seems to confirm this, but again it was concluded that the strength of the intrinsic muscles could not be isolated from that of the extrinsic muscles (31).

In our study results there was a remarkable discrepancy between the poor outcomes of the intrinsic muscles strengths as measured with the RIHM and the high levels of outcome of grip strength in patients with ulnar nerve injuries. Rosén (7) obtained similar values using the Mannerfelt intrins-o-meter and found a recovery percentage for the ulnar nerve innervated muscles of 31% and 36% for abduction of index and little finger, respectively, while the average grip strength recovery was 88%. In our study no correlation was found between the recovery of the intrinsic muscle strength and the grip strength measurements. This seems to affirm our assumption that recovery of grip strength does not reflect the recovery of the intrinsic muscles of the hand after peripheral nerve injury. Thus, outcome of the intrinsic muscle strength with the RIHM dynamometer is a valuable addition to grip and pinch strength measurements in patients with peripheral nerve injuries. The RIHM measurements might have further use in evaluation of the intrinsic hand muscle strength in, for example, leprosy, neuropathies such as hereditary motor and sensory neuropathy and Guillain-Barré syndrome.

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

Another notable finding in this study was the good recovery of the thumb intrinsic muscle strength in patients with median nerve injury, which is in contrast with the poor recovery of the abduction of little and index finger strength in patients with ulnar nerve injury. An explanation might be that the test for the thumb muscle strength is affected more by synergistic muscle activity, e.g. of the ulnar nerve innervated part of the flexor pollicis brevis muscle or due to crossover of ulnar innervation (32). Frykman et al. (26) estimated that 50% of the evaluated patients would have satisfactory thumb opposition even if no median nerve re-innervation occurred. Brand (33) mentioned another synergistic movement of the thumb palmar abduction while testing the abductor pollicis brevis due to bowstringing of the radial nerve innervated abductor pollicis longus muscle with the wrist in flexion. For this reason examiners should test the abductor pollicis brevis of the thumb with the wrist in extension. This position is not always possible with the dynamometer measurements shown in other studies but can be accomplished with the RIHM dynamometer.

A limitation in our study is that there were only 8 patients in the third group, i.e. those with both ulnar and median nerve injury. Two patients in this group had a remarkably good recovery (i.e. grip strength recovery of 98% and 91%). In 1 patient, with an ulnar and median nerve injury at the wrist level, the abduction strength of the little finger recovered to 93%. Because the results of this patient had a strong impact on the average strength of the group, we probably overestimated the average abduction strength of the little finger and the grip strength for patients with combined ulnar and median nerve injuries.

CONCLUSION

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

A dynamometer such as the RIHM provides a more accurate clinical assessment of the outcome for 2 reasons. Firstly, with the RIHM intrinsic muscle strength is measured in isolation, in contrast to grip and pinch strength measurements, in which many uninvolved muscles are tested besides the intrinsic muscles. Secondly, because of its quantitative results the RIHM measurements provide a more accurate clinical assessment as compared with the MMST, especially in MRC grades 4 and 5.

REFERENCES

1. Lundborg G. A 25-year perspective of peripheral nerve surgery: evolving neuroscientific concepts and clinical significance. J Hand Surg [Am] 2000; 25: 391–414.
2. Bruyns CN, Jaquet JB, Schreuders TAR, Kalmijn S, Kuypers PD, Hovius SER. Predictors for return to work in patients with median and ulnar nerve injuries. J Hand Surg [Am] 2003; 28: 28–34.
3. Jaquet JB, Kalmijn S, Kuypers PD, Hofman A, Passchier J, Hovius SER. Early psychological stress after forearm nerve injuries: a predictor for long-term functional outcome and return to productivity. Ann Plast Surg 2002; 49: 82–90.
4. Medical Research Council. Special Report series no 282. London: Her Majesty's Stationary Office; 1954.
5. Dellon AL. A numerical grading scale for peripheral nerve function. J Hand Ther 1993; 6: 152–160.
6. Gaul JS, Jr. Intrinsic motor recovery – a long-term study of ulnar nerve repair. J Hand Surg [Am] 1982; 7: 502–508.
7. Rosén B. Recovery of sensory and motor function after nerve repair. A rationale for evaluation. J Hand Ther 1996; 9: 315–327.
8. Rosén B, Dahlin LB, Lundborg G. Assessment of functional outcome after nerve repair in a longitudinal cohort. Scand J Plast Reconstr Surg Hand Surg 2000; 34: 71–78.
9. Rosén B, Lundborg G. A model instrument for the documentation of outcome after nerve repair. J Hand Surg [Am] 2000; 25: 535–543.
10. van der Ploeg RJ, Oosterhuis HJ, Reuvekamp J. Measuring muscle strength. J Neurol 1984; 231: 200–203.
11. Baktir A, Turk CY, Kabak S, Sahin V, Kardas Y. Flexor tendon repair in zone 2 followed by early active mobilization. J Hand Surg [Br] 1996; 21: 624–628.
12. Gault DT. Reduction of grip strength, finger flexion pressure, finger pinch pressure and key pinch following flexor tendon repair. J Hand Surg [Br] 1987; 12: 182–184.
13. Riaz M, Hill C, Khan K, Small JO. Long term outcome of early active mobilization following flexor tendon repair in zone 2. J Hand Surg [Br] 1999; 24: 157–160.
14. Boatright JR, Kiebzak GM, O'Neil DM, Peindl RD. Measurement of thumb abduction strength: normative data and a comparison with grip and pinch strength. J Hand Surg [Am] 1997; 22: 843–848.
15. An KN, Chao EY, Askew LJ. Hand strength measurement instruments. Arch Phys Med Rehabil 1980; 61: 366–368.
16. Trumble TE, Kahn U, Vanderhooft E, Bach AW. A technique to quantitate motor recovery following nerve grafting. J Hand Surg [Am] 1995; 20: 367–372.
17. Liu F, Carlson L, Watson HK. Quantitative abductor pollicis brevis strength testing: reliability and normative values. J Hand Surg [Am] 2000; 25: 752–759.
18. Mannerfelt LG. Studies on ulnar nerve compression neuropathies with a new computerised instrument – the intrins-o-meter. Scand J Plast Reconstr Surg Hand Surg 1997; 31: 251–260.
19. Schreuders TAR, Roebroeck ME, Jaquet J-B, Hovius SER, Stam HJ. Measuring the strength of the intrinsic muscles of the hand in patients with ulnar and median nerve injury; Reliability of the Rotterdam Intrinsic Hand Myometer (RIHM). J Hand Surg [Am] 2004; 29: 318–324.
20. Shaw Wilgis EF, Brushart TM. Nerve Repair and Grafting. In: Green DP, ed. Operative hand surgery: 3rd edn. New York: Churchill Livingstone; 1993, p. 1335–1336.
21. Brandsma JW, Schreuders TAR, Birke JA, Piefer A, Oostendorp R. Manual muscle strength testing: intraobserver and interobserver reliabilities for the intrinsic muscles of the hand. J Hand Ther 1995; 8: 185–190.
22. Strickland JW, Idler RS, DelSignore JL. Ulnar Nerve Repair. Gelberman RH, ed. Operative nerve repair and reconstruction volume 1 Philadelphia: J. B. Lippincott Comp; 1991, p. 425–436.
23. Tubiana R. The Hand. Vol. II. Philadelphia: WB Saunders; 1985, p. 518.
24. American Society of Hand Therapists. Clinical assessment recommendations: 2nd edn. Garner: NC; 1992.
25. Seddon HG. Surgical disorders of the peripheral nerves: 2nd edn. New York: Churchill-Livingstone; 1975.
26. Frykman GK. The quest for better recovery from peripheral nerve injury: current status of nerve regeneration research. J Hand Ther 1993; 6: 83–88.
27. Schreuders TAR, Roebroeck ME, Goumans J, van Nieuwenhuijzen JF, Stijnen TH, Stam HJ. Measurement error in grip and pinch strength measurements in patients with hand injuries. Phys Ther 2003; 83: 806–815.
28. Kozin SH, Porter S, Clark P, Thoder JJ. The contribution of the intrinsic muscles to grip and pinch strength. J Hand Surg [Am] 1999; 24: 64–72.
29. Mahaffey P. The contribution of the intrinsic muscles to grip and pinch strength. J Hand Surg [Am] 1999; 24: 870–871.
30. Stokes HM. The seriously injured hand – weakness of grip. J Occup Med 1983; 25: 683–684.
31. Janda DH, Geiringer SR, Hankin FM, Barry DT. Objective evaluation of grip strength. J Occup Med 1987; 29: 569–571.
32. Vanderhooft E. Functional outcomes of nerve grafts for the upper and lower extremities. Hand Clin 2000; 16: 93–104, ix.
33. Brand PW. Clinical mechanics of the hand. St Louis: CV Mosby; 1985, p. 239.