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Innovative methods to assess upper limb strength and function in non-ambulant Duchenne patients

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Abstract

Upper limb assessment in non-ambulant patients remains a challenge. We have designed new tools to precisely assess pinch (MyoPinch), grip (MyoGrip), wrist flexion and extension (MyoWrist) strength. We have also designed a new tool to assess the ability of patients to produce repetitive flexion/extension movements of wrist and fingers (MoviPlate). We have assessed the feasibility and reliability of these new tools in 30 non-ambulant patients with Duchenne muscular dystrophy and in 30 age-matched male controls. Existing measures, such as Motor Function Measure, Tapping, and the Brooke Upper Extremity Functional Rating Scale were also performed. Results demonstrated that assessments were feasible in nearly all upper limbs tested for MyoGrip, MyoPinch and MoviPlate. The reliability of all tests, including MyoWrist which was not feasible in the patients presenting with contractures, was excellent in patients as in controls. Motor capacities decrease with the number of months spent in the wheelchair. The scores in the tests were partially correlated with each other, and with clinical measures such as vital capacity, Motor Function Measure, functional hand scale and Brooke score. This study validates a panel of upper limb muscle strength and function measures for Duchenne Muscular Dystrophy which can be applied from controls to extremely weak patients.

Keywords: Outcome measures; Duchenne muscular dystrophy; Upper limb; Functional test; Strength

1. Introduction

During the last years, the need for accurate, reliable and sensitive outcome measures in neuromuscular patients has been persistently outlined [1,2]. Pharmaco-gene therapy is approaching the bedside for Duchenne muscular dystrophy (DMD) [3,4], the most prevalent muscular disease. For the first time in this disorder, mild motor improvement has been reported for ambulant patients under treatment [4]. In the current studies, the main functional outcome is the 6-min-walk test [4], which has been recently validated in this population [5,6]. Similar studies targeting the non-ambulant patients are critically lacking appropriate and validated assessment tools for muscle strength and motricity for the upper limb.

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Indeed, assessing upper limb in non-ambulant DMD patients is challenging, because of the combination of different aspects: extreme weakness, contractures, and several compensatory strategies that largely vary from patient to patient.

Strength of such patients may be dramatically low and problematic to assess by manual muscle testing due to its lack of sensitivity, linearity and objectivity. Quantitative muscle testing (QMT) in children with DMD [7] has been applied in a recent therapeutic trial as a secondary criterion [8]. However, this measure cannot reliably be applied to assess distal muscle function and very weak patients. Hand weakness has been assessed using a jamar grip handle but the resolution of the measurement was clearly not adapted to the patient weakness [9]. To the best of our knowledge, very sensitive dynamometers have not been evaluated yet in a population of non-ambulant DMD patients. In upper limb assessment, scales provide a more functional outcome than muscle strength measures. Several instruments have been developed to assess the upper limb functional status (see for instance [10]). Some of them have been applied to patients with DMD like the Jebsen test of hand function [11,12], or the Brooke score, a functional grade for arms and shoulders developed specifically for patients with DMD [13]. However, Lord et al. [14] underlined that "the criteria defining the functional grades of this scale do not reflect common disease stages". Jebsen hand function test has been shown to be more sensitive than the Brooke scale for the assessment of hand function among the DMD population [12].

Egen Klassification scale has been validated in spinal muscular atrophy and DMD, and is specifically designed for non-ambulant patients [15]. Reliability is excellent. The time required for the evaluation is around 15 min. This scale includes many more items than just upper limb function, such as breathing or overall well-being.

Muscle function measure (MFM) is validated in non-ambulant DMD patients and is very reliable [16]. In addition, there is a continuously expanding database running (www.motor-function-measure.org). The main problem of this scale is the time required to perform the items, which may be physically or mentally exhausting for very weak patients and for patients with attention deficit, respectively.

Recently, an 18-point-scale based on daily life tasks has been proposed for SMA, including very young children [17]. To our best knowledge, this scale has not yet been applied to non-ambulant DMD patients.

The general problem with scales is that they provide a non continuous variable with only limited possible scores, which makes their sensitivity rather low.

Correlations between muscle strength and function have already been described in patients with DMD, for example between the strength of wrist extensors and Jebsen items [11], between the overall upper limb strength and a MFM upper limb sub-score [18] or between a composite MMT score for upper limb and the Brooke scale [14].

In order to obtain reliable and sensitive outcome measures for upper limb strength, function and fatigue in non-ambulant patients, we developed specifically adapted tools, designed to be very sensitive, to be able to detect minor variation, to be applicable for patients with major contractures and to be adapted in patients with a very variable stature (growing children as well as adults). Then, we conducted a multicenter validation study (ULEnap). The aim of this study was to evaluate the feasibility and the reliability of these tools in non-ambulant DMD and other neuromuscular patients at all stages of the disease. This paper focuses on the non-ambulant DMD population.

2. Patients and methods

2.1. Patients and controls

Non-ambulant (i.e. unable to walk more than ten meters without human assistance) patients with genetically confirmed DMD ($n = 30$) and age-matched healthy control subjects ($n = 30$) were evaluated at the Institut de Myologie (Paris), Necker Hospital (Paris), Trousseau Hospital (Paris), Raymond Poincaré Hospital (Garches) and UZ Gent (Belgium). The protocol was approved by local ethic committees (ID RCB: 2009-A00600-57; B67020108468) and was registered on www.clinicaltrials.gov (2009-A00600-57). All patients or parents of minors provided informed consents before inclusion. Medical data (medical and surgical history, age when loss of ambulation, drug intake, last heart (ejection fraction) and respiratory evaluation (vital capacity), spinal deformation, intellectual disability) were reviewed from the available medical files. Inability to understand the instructions after verbal explanation and physical demonstration by physiotherapist trained with DMD patients was considered as an exclusion criterion.

In order to quantify contractures, clinicians in charge of the patients and involved in the present study agreed to rate the limitation of passive mobilization of upper limb joints as follows.

Resistance against passive mobilization of joints in flexion and extension of fingers, wrists and elbows were scored as:

0 = no resistance,
1 = resistance during passive mobilization without deformity at rest,
2 = deformity at rest, mobilization remains possible,
3 = few if any possible mobilization.

For each limb, a "passive mobility score", ranging from 0 to 18 was computed by adding the score for the flexion and extension different joints (fingers, hand, elbow). This method was adopted rather than full goniometry given the time required for the full assessment.

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2.2. Testing methods and devices

Three devices were developed to assess the strength of different muscle groups of the upper limb: MyoGrip, MyoPinch and MyoWrist. Two more functional tests were proposed to assess upper limb function: the MoviPlate test and the tapping test. The set of devices was designed as consistent and complementary ways to assess the distal motor function of the upper limb, since progressive muscle weakness tends to occur in a proximal-to-distal direction. Thus older patients may be evaluated until the later stages of their disease. Grip, pinch, wrist flexion and extension represent muscle functions that are critical to maintain a relative autonomy in electric wheelchair. The functional tests were designed to assess how the remaining strength was used for generating specific movements during repeated tasks also involving coordination, fatigue and motivation dimensions.

The MoviPlate (Fig. 1A) is a device that was designed to measure the ability to produce repeated movements between two cylindrical target keys aligned in the sagittal plane. The device is made of a platform on which the subject places his forearm. An adjustable support with one lower target and one upper target (2-cm-higher than the lower target) is adaptable to the length of the forearm. The subject is asked to press alternately the two targets as many times as possible during 30 s. Their detection threshold can be adjusted to the subjects' strength. Only back-and-forth taps are counted and displayed by the device.

The tapping device (Fig. 1B) is made of a platform on which the forearm is supported and the wrist firmly attached. Using his index, the subject must tap on a load cell (nominal scale: 10 kg; resolution: 0.001 kg) a maximum number of times during 15 s. An automatic processing of the signal enables to count the taps that are above a chosen threshold.

The MyoGrip dynamometer (Fig. 1C) is an electronic device specifically developed for measuring isometric grip strength even in weak patients. Handle size is adjustable in a continuous way. The MyoGrip measures forces from 0 to about 90 kg with a resolution of 0.01 kg.

The MyoPinch dynamometer (Fig. 1D) measures key pinch using a high precision load cell (nominal scale: 10 kg; resolution: 0.001 kg). The load cell is equipped with two steel blades 2 mm afar and presenting an overall thickness of 7 mm. The subject was asked to perform a maximal key pinch on the two blades.

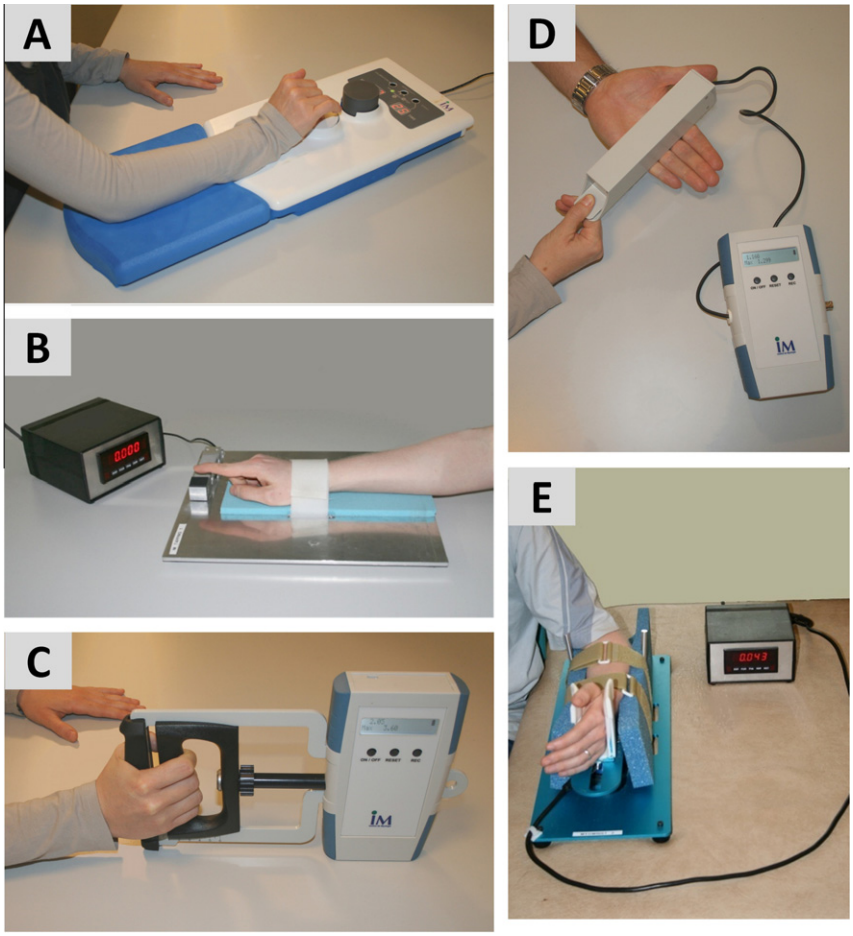

Fig. 1. Measurements tools: MoviPlate (A), tapping (B), MyoGrip (C), MyoPinch (D), and MyoWrist (E).

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The MyoWrist dynamometer (Fig. 1E) was designed to measure the isometric torque generated around the wrist axis of rotation in the flexion/extension directions.

A complete description of the tools is presented in Appendix 1.

All dynamometers are equipped with a BNC output in order to acquire the analog signal on a PC through a DAQ board for further analyses. All the transducers used in the present study and their electronic attachments were calibrated in the factories according to strict operating procedures attached to the quality assurance ISO 17025. All devices were designed and manufactured at the Institut de Myologie or by a licensed company.

In order to correlate the different scores obtained with a validated functional measure, the motor function measurement (MFM) [16] was performed once during the first session in patients only. Since patients were all non-ambulant, both the total score and the D3 sub-score were used for analysis.

2.3. Experimental protocol

The measurement sessions took place in a quiet room. Before each test, subjects were given a description of the task, a demonstration of the movement required and advice on maintaining correct practice. For strength assessment, trials were carried out with verbal encouragement asking the subjects to provide maximal voluntary isometric contractions during about 3 s. For each muscle function tested, if the difference between the first two measurements was lower than 10% of the greater, the greater was accepted. If not, a subsequent measurement was made until two trials ranged within 10%. The maximal value of two reproducible trials was accepted. If this 10% consistency criterion was not reached after 5 trials, the test was marked as "Not Achieved" (which in practice was never the case). Depending on the device, adjustments were performed to account for the stature of the subject (see Appendix 2). For the MoviPlate the position of the patient's forearm was adjusted on the plate so that the index finger was touching the center of the distal target with the hand extended. The patient was asked to hit alternatively the distal and proximal targets using the same finger or group of fingers. The arm of the patient was free, and the device was positioned to patient's best convenience. All tests were performed in the wheelchair for patients and on a regular chair for the healthy subjects.

A similar retest session was planned between 3 h and 30 days after the initial evaluation. In practice, all patients were retested between 3 h and 3 days after initial evaluation. More details on measurement procedures are given in Appendix 2.

2.4. Statistical analysis

A repeated-measure ANOVA was performed with side (non-dominant vs. dominant) and session (test vs. retest) as within-subject factors and with population (DMD boys vs. controls) as a between-subject factor. Patients and controls were compared based on the variables measured at their retest session.

Reliability was assessed in patients and controls altogether and separately by means of intraclass correlation coefficient (ICC) and standard error of measurement (SEM). $ICC_{2,1}$ was computed as a single measure ICC with a two-way random-effect model (absolute agreement). ICC between 0.70 and 0.90 were considered as highly reliable and ICC between 0.90 and 1.00, as very highly reliable. SEM was computed as the standard deviation (SD) of the differences between test and retest values divided by the square root of 2. The SEM is a measure of absolute reliability and is expressed in the actual units. Relative SEM (%) was computed as absolute SEM divided by the mean value of the measure.

In order to assess potential learning or fatigue effect, test and re-test results were compared using student t tests for paired values. If this test was significant, a learning curve was computed by comparing each trial with the preceding trial, regardless of the session number (a session may present 2–4 trials). The difference between two consecutive trials was normalized by the result of the previous trial.

First, correlations between strength (grip, pinch, and wrist flexion and extension strength) and functional tests (MoviPlate, tapping, MFM) were studied. Second, correlations between strength and functional tests and different clinical outcomes were tested. Clinical outcomes tested were age, duration since loss of ambulation, weight, height, forced vital capacity, ejection fraction, Brooke score and passive mobility score. All correlations were assessed using Spearman's rank correlation coefficient as relationships between variables might not be linear.

All analyses were performed using the SPSS 15 statistical software (SPSS Inc., Chicago, IL). The limit of statistical significance was set to 0.05.

3. Results

3.1. Clinical features

Age of patients and controls was 16.8 ± 4.4 [10.0–27.7] years and 16.3 ± 5.5 [8.2–27.8] years, respectively. Clinical features are given for all patients in Table 1. One patient started the assessment, but according to the evaluator, was not able to maintain sufficient attention to provide reliable data. This patient was excluded of the study and his results are not reported below.

The mutations were an exonic deletion in 17 cases, a duplication in 2 cases, a premature stop codon in 6 cases, a base deletion in 3 cases and a base insertion in 2 cases. Intellectual disability was clinically noted in 43% of the patients but formal IQ was available only for a minority. Among patients reported as intellectually disabled, 10 attended a special education program and two could not attend school. Five patients were on steroids. The patients

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Table 1
Demographic data of patients.

	Age (years)	Deletion	Height (cm)	Weight (kg)	Steroid	Age at ambulation loss (years)	Arthrodesis	Contractures	Educational backwardness	VEF (%)	FVC (%)	Brooke score (#)
103	18.2	del49–50	160	58	0	8.0	1	1	0	60	17	5
104	13.8	del31–43	176	90	0	11.0	0	1	0	50	57	3
106	26.7	del51	162	73	0	11.0	1	1	0	45	14	5
108	13.8	c.10453dup	160	54	0	12.5	0	0	0	66	101	2
110	15.9	del45	166	32	0	9.9	0	1	0	50	47	5
111	12.1	del3–44	161	39	0	9.8	0	1	1	60	43	5
114	23.9	del42–44	173	71	0	10.5	1	1	0	50	26	5
116	16.6	c.4084C>T	175	68	0	8.3	1	1	0	65	50	5
117	27.7	del45–54	164	48	0	12.0	0	1	0	50	12	5
201	10.0	c.7392delC	140	29	0	7.0	0	0	1	71	104	4
301	14.4	c.7657C>T	155	28	0	9.8	1	1	1	64	41	5
302	19.5	c.2638delC	171	67	0	9.8	1	1	0	68	18	5
303	18.8	c.10722delC	147	32	0	NA	1	1	1	NA	72	5
304	15.5	c.998C>A	166	40	0	14.1	1	1	0	50	40	5
305	15.7	del42–54	155	29	0	13.0	1	1	1	NA	33	4
306	13.7	del48–54	162	74	0	10.3	1	1	1	57	27	3
307	18.1	del 45–54	170	50	0	11.3	1	1	1	NA	37	5
309	11.6	c.998C>A	151	35	0	9.7	0	1	1	64	58	5
310	15.7	del10–11	150	30	0	10.0	1	1	1	65	41	5
311	17.7	c.6364G>T	158	23	0	7.6	1	1	0	71	12	5
312	12.9	del46–49	140	34	0	10.3	1	1	1	59	48	5
401	16.0	c.4870C>T	NA	58	0	8.0	1	1	0	35	63	5
402	17.8	c.7858dup	164	43	1	11.3	1	1	0	62	33	5
403	14.2	dup2–5	154	47	0	9.0	0	0	0	35	63	5
404	10.8	del53	135	33	1	10.2	0	1	1	64	90	2
504	15.2	del8–9	171	52	0	8.3	1	1	0	60	64	5
507	22.4	del47–51	160	50	0	8.5	1	1	1	59	23	6
508	20.1	del51–60	NA	90	0	11.1	1	1	1	60	49	5
509	22.0	del8–43	172	46	0	10.4	1	1	0	35	14	6
511	12.2	dup8–11	158	55	1	9.0	0	NA	0	61	65	4

0: no – 1: yes
NA: not available
FVC: forced vital capacity
VEF: ventricular ejection fraction

had lost ambulation at a mean age of 10.0 ± 1.6 years, which corresponded to a gait loss for 6.7 ± 4.4 years at the moment of inclusion. Thirty-three percent of the patients used non-invasive ventilation, between 6 and 23 h a day. None of the patients had invasive ventilation. Spinal arthrodesis had been performed in 68% of the patients (mean age at surgery: 13.7 ± 1.8 years). The left ventricular ejection fraction was reduced to less than 55% in nine patients. The forced vital capacity value was reduced to $45.4 \pm 25.1\%$ of the normal reference values. The mean Brooke score of the patients was 4.63 ± 0.96. The mean passive mobility score was 6.31 ± 3.41 on the non-dominant side and 6.34 ± 3.44 on the dominant side.

3.2. Feasibility

The whole evaluation process took between 40 min for the control subjects and 70 min for the most disabled patients. All the patients were able to perform the MFM, MyoGrip, MyoPinch. All but two patients were able to perform the MoviPlate test. One patient could not perform all the tests with his non-dominant limb, because of major contractures. Strength devices were able to detect strengths as low as 0.05 kg for grip and 0.07 kg for key pinch. The tapping test was feasible for 24 patients and wrist strength assessment could be performed in half of the patients only.

In order to test the effect of strength and contractures on patients who could not perform all the tests, we compared the grip strength and the passive mobility score between the group of subjects having performed the MyoWrist and those who had not. The results show that there is a significant contracture effect between both groups but no strength effect. Also, the differences of Brooke's score and of age between patients who were able to perform the MyoWrist and patients who were not able were not significant. The same test was performed between the group of subjects having performed the tapping test and those who had not. The results show that there is no significant contracture effect but a significant strength effect between both groups.

There was no particular pattern of contractures that was limiting the feasibility of tapping or MyoWrist tests.

3.3. Dominance effect

Patients and controls scored significantly higher on the dominant side for grip, pinch and MoviPlate tests. No

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Table 2
Reliability parameters for patients (A) and controls (B).

A	Mean	Mean difference	SEM	ICC	ICC 95%CI
Grip strength (kg)	3.29	−0.12	0.32	0.98	0.97–0.99
Key pinch (kg)	1.23	−0.04	0.17	0.96	0.93–0.98
Wrist flexion (Nm)	1.23	−0.07	0.25	0.94	0.88–0.97
Wrist Extension (Nm)	0.98	−0.02	0.20	0.95	0.90–0.98
MoviPlate (#)	42.35	2.51*	3.92	0.92	0.84–0.96
Tapping (#)	49.63	−1.20	5.29	0.89	0.80–0.94
B	Mean	Mean difference	SEM	ICC	ICC 95%CI
Grip strength (kg)	33.41	−0.33	1.98	0.98	0.97–0.99
Key pinch (kg)	6.36	−0.22*	0.37	0.92	0.85–0.96
Wrist flexion (Nm)	10.14	−0.23	0.88	0.94	0.91–0.97
Wrist Extension (Nm)	7.56	−0.09	0.81	0.92	0.87–0.95
MoviPlate (#)	74.70	3.55*	4.05	0.89	0.73–0.95
Tapping (#)	76.88	0.45	2.78	0.95	0.91–0.97

* p-Value < 0.05.

dominance effect was observed for wrist flexion and extension and tapping tests.

3.4. Reliability

Reliability parameters were computed for each population separately (Table 2). All the measurements showed high to very high reliability according to ICC values (all ICC > 0.8). Correlations between test and retest sessions are displayed in Figs. 2a (A–C) and 2b (D–F). Reliability for all tests was not significantly lower in patients with intellectual disability in comparison with patient without intellectual disability.

3.5. Learning effect

Paired Student's t tests did not reveal any significant difference between test and retest scores in all strength tests. A significant difference between test and retest sessions was observed for patients for both dominant (2.0 ± 6.4) and non-dominant (3.0 ± 4.6) limb for the MoviPlate, demonstrating a mild but significant learning effect. A similar effect was observed in controls for dominant (3.9 ± 6.0) and non-dominant (3.2 ± 5.6) limb.

Learning curve demonstrated an improvement of 10.1% for the second trial when compared with the first, which fell from trial to trial down to 1.9% when comparing the 5th with the 4th trial, which means that a plateau was reached.

3.6. Comparison between patients and controls (Table 2)

All the motor performances were lower in the patients than in the controls (all p values < 0.0001). All the tests were highly discriminating with minor overlap between controls and patients.

3.7. Correlations between strength and functional tests (Table 3)

All strength and functional tests were significantly correlated (rho ranging between 0.52 and 0.87).

3.8. Correlation between clinical, strength and functional variables (Table 4)

All tests but tapping were significantly inversely correlated with age (rho from −0.41 (wrist flexion) to −0.84 (MFM)). All tests were significantly inversely correlated with duration since loss of ambulation, (rho from −0.33 (tapping) to −0.86 (MFM)). All correlations between the different tests and "duration since loss of ambulation" were stronger than between the tests and the age.

There was no significant correlation between height and weight and the strength tests and functional tests except for the tapping which was significantly correlated with both (rho = 0.31 for height and rho = 0.39 for weight).

All tests were significantly correlated with forced vital capacity (rho from 0.29 (MoviPlate) to 0.74 (MFM)). In contrast, no test except wrist flexion and extension was correlated with ejection fraction. All tests were negatively correlated with Brooke score (rho from −0.31 (MoviPlate) to −0.81 (wrist extension)).

Tests that could be performed in nearly all patients, namely MyoGrip, MyoPinch and MoviPlate were not correlated with the passive mobility score. In contrast, wrist flexion and extension torques were significantly correlated with passive mobility score.

4. Discussion

We have demonstrated that sensitive dynamometers and specifically designed functional tests allow very reliable measures of strength and function for healthy subjects as well as for very weak DMD patients, who may present with major contractures.

We believe that the studied population is representative of the non-ambulant DMD population (except for patients with severe intellectual disability), since patients were selected from the consultations of large neuromuscular centers, without evident bias, since the age was normally distributed between 10 and 30, and since respiratory and cardiac involvement was comparable with another recent series [19]. All but one of the patients who were proposed to take

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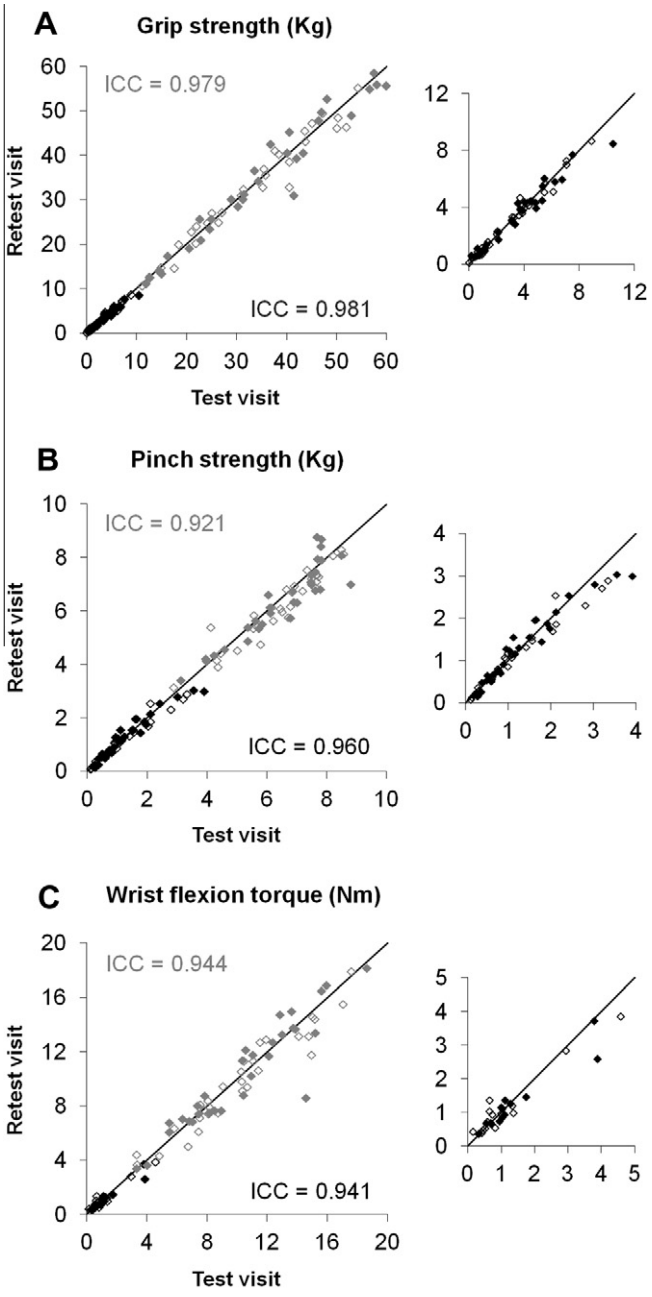

Fig. 2a. Reliability between test and retest sessions for grip (A), pinch (B), and wrist flexion torque (C). (◇) Controls non-dominant side (◆) controls dominant side (◇) patients non-dominant side (♦) patients dominant side. An expended scale focused on patients is presented for each test.

part in the study were able to understand the instructions, and to provide repeatable results, but the study was not proposed to patients who were obviously not able to cooperate for the assessment. Therefore, it is thus not possible to accurately estimate the percentage of the population who is not able to understand the instructions and/or to provide reliable data. However, we do not believe that this percentage is significantly higher than for any simple assessment.

A strength measurement is expected to be reliable, as measured by ICC, possible in all ranges of patients from the strongest to the weakest ones, including patients with contractures, and sensitive enough to detect minor changes in patient condition in very weak forces range. MyoGrip and MyoPinch meet these requirements. In comparison with traditionally used tools, they are much more sensitive.

MyoWrist was applicable for only one half of the patients, but was reliable in this population and highly discriminates from controls. It appears that contractures constitute the limiting factor for the feasibility of this test. This is probably related to the fixation of the patients arm in a standard position that does not take into account the specific contracture pattern of each patient. Tapping also appears to be a reliable test, but it is not feasible in the weakest patients.

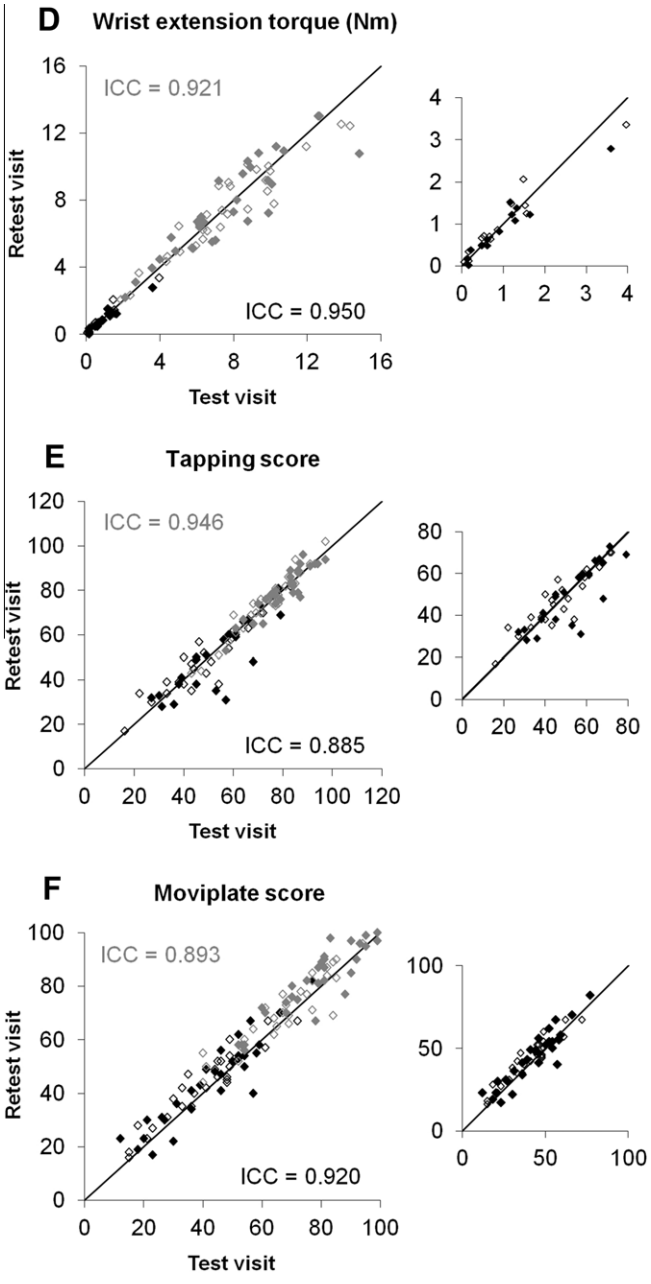

Fig. 2b. Reliability between test and retest sessions for wrist extension torque (D), tapping (E), and MoviPlate (F). Same legend than in Fig. 2a.

Table 3
Correlations between strength and functional tests in patients.

	Handgrip (kg)	Key pinch (kg)	Wrist flexion (Nm)	Wrist Extension (Nm)
MoviPlate (#)	0.569**	0.516**	0.613**	0.660**
Tapping (#)	0.649**	0.597**	0.615**	0.554**
MFM D3 (#)	0.831**	0.806**	0.733**	0.591**
MFM (#)	0.874**	0.854**	0.769**	0.795**

** p-Value < 0.01

It is already known that hand strength in DMD decreases with age, and is significantly different in comparison with controls [9]. Our results confirm this data.

It is not so straightforward that strength is directly correlated with function and moreover with quality of life. Therefore, functional tests, such as scales or clinical tests may be preferred as outcome measures in clinical trials. However, it must be noted that in the present study, we have demonstrated a significant non-linear correlation between strength and functional or clinical parameters, such as CV or Brooke score. Moreover, since distal strength of prehension through grip and pinch and motor function of moving fingers are cardinal for non-ambulant patients' autonomy (driving the wheelchair, writing, using computer or phone), we believe that measuring pinch and grip strength and ability of moving finger is clinically meaningful.

Grip and pinch strengths were generally assessed using the Jamar grip handle (Patterson Medical/Sammons Preston Corporate, Bolingbrook, IL, US) and the B&L pinch gage (B & L Engineering, Santa Ana, CA, US), respectively. These dynamometers are graduated every 2 kg and 1 kg, respectively. Weak patients cannot obviously be evaluated when their strength falls under the minimal graduations. Grip strength and pinch strength are known to be severely decreased in DMD patients compared to healthy controls, even in ambulant patients [9,11,20], and decrease with age [9,18], which is consistent with our findings. In one study, grip strength and pinch strength of several patients between 12 and 22 years could not be discriminated from zero, due to the lack of sensitivity of the dynamometers used [11]. This precludes their use in therapeutic trials as an outcome measure in very weak patients. In contrast, neither MyoGrip nor MyoPinch presented a floor effect, even for the weakest patients. They could be rapidly and reliably performed in very weak patients, and are not correlated with contractures.

In contrast with isometric wrist extension and flexion, isometric grip and pinch are motor tasks frequently used in daily life. For this reason, they are much more naturally understood and achieved by patients, which is even more evident in children.

The MoviPlate allows rapid, reliable and objective assessment of hand mobility and timed motor performance. The outcome is correlated with strength measure of distal functions of the upper limb, and does not present floor or ceiling effects. In addition, this test discriminates 10 year-old DMD patients and controls. We observed a mild, but significant learning effect between test and retest sessions, in patients as well as in controls. Learning effect is often considered in functional assessment, including the six-min-walk test, but may be considered as minimized by a training session for the patient before the baseline assessment [4]. However, this learning effect may constitute a confounding factor that could decrease the sensitivity for negative change, or induce false positive evolution through time. We therefore recommend to allow the patient to have a training session of several trials before the baseline.

Some correlations between strength and autonomy have been pointed out in DMD [21], and in patients with other neurological conditions [22,23]. Here, we demonstrate that the functional performance in patients, measured by MFM, tapping or MoviPlate, is correlated with the strength of hand grip and key pinch.

This is in line with other observations that correlate strength as measured by MMT and scales such as Brooke [14] or MFM [18]. The correlation between MoviPlate score and strength measurement is much weaker in controls, probably because strength is not the limiting factor for a repetitive timed motor task factor in controls.

Strength and functional scores were correlated with indices of severity of the disease, such as a decrease in vital

Table 4
Correlations between clinical, strength and functional variables in patients.

	Handgrip (kg)	Key pinch (kg)	Wrist flexion (Nm)	Wrist Extension (Nm)	MoviPlate (#)	Tapping (#)	MFM D3 (#)	MFM (#)
Age (years)	−0.628**	−0.702**	−0.413*	−0.534**	−0.444**	−0.167	−0.663**	−0.836**
Duration since loss of ambulation (years)	−0.707**	−0.716**	−0.728**	−0.735**	−0.530**	−0.333*	−0.691**	−0.858**
Weight (Kg)	0.007	0.078	−0.043	0.043	0.019	0.391**	0.0003	−0.131
Height (cm)	−0.019	−0.141	−0.265	−0.154	0.175	0.313*	−0.155	−0.310*
FVC (%)	0.590**	0.712**	0.496**	0.674**	0.292*	0.335*	0.606**	0.742**
VEF (%)	−0.012	0.166	0.413*	0.642**	−0.038	−0.0002	−0.051	0.096
Brooke score (#)	−0.606**	−0.695**	−0.770**	−0.813**	−0.311*	−0.414**	−0.503**	−0.728**
Contracture score (#)	−0.167	−0.213	−0.508*	−0.594**	−0.266	−0.047	−0.281*	−0.455**

FVC: Forced vital capacity
VEF: Ventricular ejection fraction
* p-Value < 0.05.
** p-Value < 0.01.

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capacity, Brooke score, and time since the loss of ambulation. Interestingly, we did not find any significant relation between the passive mobility score and the tests that could be performed even in patients with major contractures. We believe that this is due to the fact that patients are not constrained during these tests (in contrast with MyoWrist and tapping) and can therefore adapt their motor strategy to optimize their score.

This study demonstrates that Myogrip, MyoPinch and MoviPlate scores should be considered as outcome measures in non-ambulant DMD boys, since they are clinically meaningful, sensitive, reliable, rapid and do not present ceiling effects in this population, or in the control population where they can also be used. MoviPlate showed a mild floor effect for the two weakest patients. In addition, these tests evaluate different group of muscles in the distal area of the upper limb, which explains the partial correlations between them. They are therefore complementary to evaluate distal upper limb function. They are rapid and straightforward to perform, the assessment of both arms by these three tests only takes about 20 min. MyoWrist and tapping constitute also reliable assessment in DMD patients, but can only be used in a limited number of patients and may therefore constitute a limiting inclusion factor. A prospective longitudinal study is ongoing to assess the sensitivity to change of these different methods and to evaluate these tools in other neuromuscular disorders.

Conflict of interest

JYH is inventor of the patented MyoGrip. JYH and AM are inventors of the patented MyoPinch. JYH, AC, TV and LS are inventors of the patented MoviPlate.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.nmd.2012.10.022.

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