Quantifying Human Muscle Strength, Endurance and Fatigue

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Physiologic methods have been developed to objectively quantify muscle strength, endurance, and fatigability. Isometric force and rectified/integrated electromyogram were simultaneously recorded during the three phases of a recording session: (i) pre-fatigue, (ii) fatigue (1min duration) and (iii) post-fatigue recovery (up to 10min). Five parameters of muscle performance were computed: (1) Maximum force (MF) exerted during isometric voluntary contraction (muscle strength); (2) Force-time integral—area under force-time plot (endurance); (3) Fatigue index (FI) (% reduction in MF); (4) Neuromuscular efficiency (force/mV of EMG recruited), and (5) Recovery time (RT). Normal values based on data from 20 normal subjects were determined for four muscles: index finger abductor, elbow flexors, knee extensors, and ankle dorsiflexors. Neuromuscular efficiency (NME) decreased significantly (20 to 70%) at the end of the fatigue phase; it generally increased to the pre-fatigue level in 2 to 10 min, during the recovery phase. The period needed to reach pre-fatigue level was referred to as RT. The elbow flexors had the highest mean FI (48%) and the longest RT (>6min); the ankle dorsiflexors had the lowest mean FI (34%) and the shortest RT (1.5min). These methods have been used also to evaluate the effects of weight training in two patients with neuromuscular disorders.

KEY WORDS: Fatigue; Muscles; Muscular dystrophy; Neuromuscular diseases

Objective methods of quantifying muscle strength, endurance, and fatigue are needed in the evaluation of patients with neuromuscular disorders, since weakness and fatigability are major symptoms.

Muscle fatigue, a common complaint, has been particularly difficult to analyze. Tests involving repetitive nerve stimulation are virtually the only current methods for studying muscle fatigue; these are usually normal in patients with muscle or nerve disorders. Dynamic measures of muscle force, fatigue, and recovery are ignored by such tests.

There is a lack of agreement concerning the effectiveness of active muscle strengthening programs in neuromuscular disease rehabilitation2,7,23, the conflicting reports resulting partly from lack of objective methods of quantifying muscle performance.

This investigation purposed to develop reliable and reproducible methods of measuring muscle strength, endurance, fatigue, and the time course of post-fatigue recovery by studying four muscles in healthy subjects. Methods, data from 20 subjects, and examples of quantitative evaluation of the effects of weight training in two patients with muscular dystrophy are described.

METHODS

Subjects. For each muscle, an equal number of men and women were studied. Ages ranged from 18 to 52 years and weight from 57 to 80kg in the men and from 21 to 45yr and 50 to 65kg in the women.

A. Force and EMG Measurements

First Dorsal Interosseous (FDI) Muscle. The subject was comfortably seated, with the right arm resting on a board on which a force transducer4, a hand stabilizer, and arm straps were mounted. The index finger was held in a metal bracket attached to the transducer at the proximal interphalangeal joint, and the thumb was stabilized at an abduction angle of approximately 90°. The arm was strapped to the board at the wrist and forearm. One surface electrode was firmly taped to the belly of the FDI and another on the lateral aspect of the metacarpophalangeal joint of the index finger for recording muscle potentials; a ground electrode was taped to the back of the hand.

Elbow Flexors. Subject was comfortably seated, arm supported in a specially designed device in which the angle between the upper arm and forearm was maintained at 90° to ensure a consistent isometric contraction. The force transducer was mounted under a platform with a wrist strap; the position of the structure (transducer, platform, wrist strap) could be adjusted to accommodate different forearm lengths. The rest of the apparatus included a mounting board, attached to a pulley permitting vertical adjustments. The upper arm was strapped to a vertical support, at two positions 10cm apart. The lower strap was close to the elbow while the other was around the most proximal region of the biceps. Acetonel-soaked gauze was used to clean the skin before taping surface recording electrodes, while the ground electrode was placed on the lateral epicondyle of the humerus.

Ankle Dorsiflexors. Subject was seated on a table, with the right leg on a platform attached to the force transducer assembly. One end of the platform was shoe-shaped to hold the heel.
Table 1: Summary of Neuromuscular Function Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Computation*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Maximum Force</td>
<td>MF(N)</td>
</tr>
<tr>
<td>2. Force-Time Integral (FIT)</td>
<td>( t \cdot \text{Area under force-time plot (N.s)} + \text{BW(kg)} )</td>
</tr>
<tr>
<td>3. Fatigue Index (FI)</td>
<td>( \frac{MF(I) - MF(60)}{MF(I)} \times 100 )</td>
</tr>
<tr>
<td>4. Rectified Integrated Electromyogram (RIEMG)</td>
<td></td>
</tr>
<tr>
<td>5. Electromyogram Augmentation (EMG(_{\text{aug}}))</td>
<td></td>
</tr>
<tr>
<td>6. Neuromuscular Efficiency (NME)</td>
<td></td>
</tr>
<tr>
<td>7. Recovery Time (RT)</td>
<td></td>
</tr>
</tbody>
</table>

Symbols: N = Newton; BW = body weight; N.s = Newtons-seconds; MF = max force.

Table 2: Summary of Maximum Forces and Force-Time Integrals (per Kg Body Weight) of 4 Muscles

<table>
<thead>
<tr>
<th>Muscle</th>
<th>BW (N/kg)</th>
<th>Force-Time Integral/BW (N-set/kg)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Males</td>
<td>Females</td>
</tr>
<tr>
<td>First dorsal interosseous</td>
<td>0.5 ± 0.07</td>
<td>0.41 ± 0.09</td>
</tr>
<tr>
<td>(( \bar{x} + \text{SD}[n=10] ))</td>
<td>0.42 ± 0.61</td>
<td>0.28 ± 0.53</td>
</tr>
<tr>
<td>Elbow flexors</td>
<td>3.89 ± 0.71</td>
<td>2.63 ± 0.68</td>
</tr>
<tr>
<td>(( \bar{x} + \text{SD}[n=12] ))</td>
<td>2.94 ± 5.36</td>
<td>1.63 ± 3.53</td>
</tr>
<tr>
<td>Ankle</td>
<td>5.04 ± 0.42</td>
<td>4.49 ± 0.37</td>
</tr>
<tr>
<td>(( \bar{x} + \text{SD}[n=11] ))</td>
<td>4.15 ± 5.7</td>
<td>3.81 ± 5.2</td>
</tr>
<tr>
<td>Knee extensors</td>
<td>8.3 ± 15</td>
<td>7.2 ± 1.3</td>
</tr>
<tr>
<td>(( \bar{x} + \text{SD}[n=10] ))</td>
<td>6.62 ± 10.9</td>
<td>5.45 ± 8.9</td>
</tr>
</tbody>
</table>

Force and EMG Recording

The force transducer signal was amplified and fed into a voltmeter to provide visual feedback to the experimental subjects. The surface EMG was recorded with 10mm disc electrodes attached to one end of the table. The transducer assembly was connected to an ankle brace, consisting of a padded, curved metal plate, with a Velcro strap and a belt buckle. The knee angle was held at 90° with the ankle firmly strapped to the transducer assembly. Surface recording electrodes were placed over the belly and tendon of the rectus femoris.

Table 3: Summary of Fatigue Index, EMG Augmentation and Neuromuscular Efficiency of 4 Muscles, from 20 – 24 Combined Male and Female Subjects

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Fatigue Index (%)</th>
<th>RIEMG Augmentation (%)</th>
<th>% Decrease</th>
<th>Recovery Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First dorsal interosseous</td>
<td>42 ± 15</td>
<td>40 ± 15</td>
<td>32 ± 12</td>
<td>3.1 ± 1.9</td>
</tr>
<tr>
<td>(( \bar{x} + \text{SD}[n=20] ))</td>
<td>20 – 63</td>
<td>20 – 70</td>
<td>16 – 60</td>
<td>1 – 6</td>
</tr>
<tr>
<td>Elbow flexors</td>
<td>48 ± 14</td>
<td>71 ± 43</td>
<td>49 ± 15</td>
<td>6.6 ± 3.8</td>
</tr>
<tr>
<td>(( \bar{x} + \text{SD}[n=24] ))</td>
<td>22 – 80</td>
<td>21 – 198</td>
<td>20 – 71</td>
<td>2 – 10</td>
</tr>
<tr>
<td>Ankle</td>
<td>34 ± 12</td>
<td>45 ± 20</td>
<td>31 ± 14</td>
<td>1.4 ± 0.4</td>
</tr>
<tr>
<td>(( \bar{x} + \text{SD}[n=22] ))</td>
<td>14 – 55</td>
<td>20 – 133</td>
<td>12 – 54</td>
<td>0.5 – 2</td>
</tr>
<tr>
<td>Knee extensors</td>
<td>46 ± 15</td>
<td>54 ± 36</td>
<td>49 ± 13</td>
<td>5.9 ± 3.9</td>
</tr>
<tr>
<td>(( \bar{x} + \text{SD}[n=20] ))</td>
<td>21 – 78</td>
<td>18 – 131</td>
<td>30 – 70</td>
<td>2 – 10</td>
</tr>
</tbody>
</table>

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Neuromuscular Efficiency (NME) = \frac{\text{Force (N)}}{\text{RIEMG (mV)}}

Fig 2—Three typical 5-sec recordings of 50% maximum force (MF) and rectified/integrated electromyogram (RIEMG) from one subject: A. Pre-fatigue. B., C. Post-fatigue, at 5 sec and 60 sec of recovery phase. Neuromuscular efficiency (NME) values shown are mean of 5 values measured at 1-sec intervals. Force tracing is rectangular and of similar size and shape in each tracing (50% of maximum).

trodes, connected to a pre-amplifier and then to an amplifier (bandpass filter settings 1.6Hz to 16kHz). The amplifier was modified to provide rectification and integration of the EMG signal. Both the FORCE and EMG signals were recorded on an FM tape recorder for data analyses.

C. Fatigue Protocol

Pre-Fatigue Phase: After determining the maximum isometric force, subject was asked to exert 100% and 50% of MF for 5 sec each, using the voltmeter reading as feedback; the recorded data represent the pre-fatigue phase.

Fatigue Phase: Subject was asked to exert and maintain MF for 1 min.

Post-Fatigue Recovery Phase: After 1 min of fatigue, subject was asked to relax for 2 sec and to subsequently exert 50% of MF for 5 sec at the following time intervals after fatigue: 2, 15, 30, and 45 sec; 1, 1.5, 2, 3, 4, 6, and 10 min.

D. Data Analyses

Definitions, abbreviations, units, and methods of computation are summarized in table 1. A computer was used for data analyses. The six parameters computed were: 1. force (Newtons—N), 2. amplitude (mV) of the rectified/integrated
dry surface electromyogram (RIEMG), 3. neuromuscular efficiency (N/mV), 4. fatigue index (%) (FI), 5. force-time integral (N.s) and 6. EMG augmentation (%). Neuromuscular efficiency = \frac{\text{Force (N)}}{\text{RIEMG (mV)}} was computed from 5-sec records of Force and RIEMG at 1-sec intervals and the mean determined for each. The mean NME was computed for the pre-fatigue muscle and intervals during recovery.

These methods are now used routinely in our Neuromuscular Research Laboratory to determine the level of muscle performance in patients with neuromuscular disorders and, more importantly, to objectively evaluate the effects of weight training and other therapeutic modalities; two patients will be presented as illustrations: pt 1. a 42-year-old man with fascioscapulohumeral muscular dystrophy and pt 2. a 23-year-old man with Becker muscular dystrophy.

RESULTS

Data from the four muscles of the normal subjects are summarized in tables 2 and 3; table 2 summarizing by sex the MF and FTI in relation to body weight (BW). In table 3, however, FI, EMGaug, and NME data of all subjects are combined, as these parameters were independent of BW or sex. Representative data from two men (M1, M2) and two women (F1, F2) are plotted for the elbow flexors to illustrate the time-course of fatigue and recovery (figs 1 and 3).

Fatigue Phase. There was a qualitatively similar pattern of fatigue for all subjects. The force of maximum voluntary con-
The effect of 3 years weight training with dumbbells on muscle performance: 1) Maximum Force (N); 2) Force-Time Integral (N.s); 3) Fatigue Index (FI). Patient 1: JG Facioscapulohumeral Muscular Dystrophy. Patient 2: FM Becker Muscular Dystrophy. The elbow flexors were the most fatigable muscles (FIx = 48 ± 14%) and the ankle dorsiflexors the least (FIx = 34 ± 12%). Similarly, the greatest reduction in NME was found in the elbow flexors (x49 ± 15%) and the smallest in ankle dorsiflexors (x31 ± 14%).

The greatest EMG augmentation (x 71 ± 43%) occurred in the most fatigable muscle group, the elbow flexors. The strongest muscle group, the knee extensors (MF/BW x 8.3 ± 1.5 N/kg (males), 7.2 ± 1.3 N/kg (females)) performed the most work (FTI/BW x 377 ± 74 N.s/kg (males), 334 ± 80 N.s/kg (females)), but were almost as fatigable as the elbow flexors (x fatigue index 46 ± 15%). Thus, the data on fatigue are internally consistent between muscles.

Post-Fatigue Recovery Phase: NME is used to quantify the time-course of recovery: a typical 5-sec record of 50% MF and RIEMG during pre-fatigue and after the end of 1 min of fatigue recorded from 1 subject (fig 2) shows a 57% decrease in NME from 130 N/mV (prefatigue) to 56 N/mV (5 sec post-fatigue) and a partial recovery at 60 sec of the recovery phase. A plot of the time course of recovery of NME recorded from the elbow flexors of four subjects (fig 3) after 60 sec of fatigue for 3 subjects (M1, M2, F2) shows complete recovery in 2 min, with M1 and M2 showing further improvement in NME above control levels; while subject F1 attained an incomplete recovery of 83% during 10 min of recovery. Summaries of recovery times are shown in the last column of table 3: the slowest recovery was observed in elbow flexors (x 6.6 min), and fastest recovery in ankle dorsiflexors (x 1.4 min).

Reproducibility. Although there were variables in all parameters among subjects, the two most important parameters, MF and FTI, were particularly reproducible, when the same subject was tested two or three times. Reproducibility was statistically documented in the FDI of two subjects (the authors) who were tested 12 times on four occasions within a 6-month period. Although there might have been some cumulative fatigue on each occasion because three 1-min fatigue (and recovery, tests were done in 2 hr, the mean ± SD of MF and FTI from the two subjects were 1) 32 ± 2.6 N and 1778 ± 82 N.s and 2) 30.3 ± 2.1 N and 1642 ± 57 N.s, respectively. A third subject was tested five times on two occasions, with a corresponding mean ± SD of 32 ± 2 N and 1653 ± 103 N.s: the mean deviation of 6% demonstrates excellent reproducibility.

Muscular Dystrophy Patients: The Effects of Weight Training

Patient 1: (weight 75 kg): At age 39, there was no measurable force from his right elbow flexors: his left elbow flexors could generate a MF of 55 N or 0.72 N/kg (19% mean control). The effect of weight training with dumbbells on muscle performance during a 3-year period is shown in fig 4. Peak improvement in muscle performance occurred after 16 months of 3 to 4 times/wk weight training. Muscle strength doubled, while work capacity (FTI) improved by 150%: fatigue index initially 65% (normal 49 ± 15%) also improved (range = 34 to 51%), although greater work loads were maintained.

Patient 2: When the initial muscle performance tests were done at age 19, the patient weighed 43 kg: right elbow flexors were stronger (65 N, or 1.5 N/kg) than left elbow flexors (50 N, or 1.16 N/kg: 30% mean control). Left elbow flexors were therefore selected for weight training, using a 2-kg dumbbell, progressively increasing to a 4.5-kg. The effects of 3 yr, 4 days/wk weight lifting by left elbow flexors compared with the nonexercised right elbow flexors are plotted (fig 4). The strength of the left elbow flexors doubled, and the FTI increased by 250%. Improvements of 18% (strength) and 90% (FTI) which occurred in the nonexercised right elbow flexors may be attributed to both transfer effect15,32 and to the 10% weight gain. The fatigue index of the exercised left elbow flexors improved from 75% to a peak of 28%.

Discussion

Since muscle weakness is one of the primary symptoms of most neuromuscular disorders, it is important to quantify mus-
Muscle strength to determine the extent of muscle weakness, to objectively assess the progress of the disease, and to quantify the efficacy of therapy.

The MF generated by a muscle depends on the number and size of muscle fibers as well as the extent of use or disease. Despite these variables, the MF of a patient provides an estimate of residual muscle strength when compared with corresponding mean control values.

Although the force-time integral depends on the maximum force and fatigue index, it is an independent, quantitative measure of the total work load that a muscle can sustain in a specific period; it is proportional to the energy consumed and will to some extent determine the recovery time for the muscles. For example, two control subjects generated maximum elbow flexion (MF) and FTI of 187N, 7250 Ns and 166N, 7950 Ns respectively; the latter subject whose MF was 21N less, but who generated 700N.s FTI more than the former, recovered only 83% in 8min, while the other recovered in 2min. To some extent, FTI is also a quantitation of effort. It could be argued that lack of motivation could give a spuriously large FTI. However, the changes in NME, the time course of recovery and the FTI when taken together permit the ready identification of inadequate effort.

Fatigue Index is a measure of the reduction in the force-generating capacity of the muscle; both the FTI and FI are therefore quantitative measures of muscle endurance. For each muscle-group data there was a wide range in the FI, and there were also clearcut differences between muscles. It has been reported that muscles with a high percentage of fast twitch (type II) fibers, generate greater MF and fatigue faster than muscles with a high percentage of slow twitch (type I) fibers; this is consistent with the 58-64% type II fiber composition of biceps brachii compared to 73% type I fiber composition of anterior tibialis. The wide range of FI within the same muscle group may have been partly due to the variations in the fiber composition among individuals.

After 1min of maintained muscle contraction, several metabolic changes occur: high energy phosphates are reduced, lactate accumulates, resulting in a decrease in pH, and K⁺/Na⁺ gradients across muscle membranes are altered. The combined effects of these changes result in fatigue — a reduction in the force generating capacity of the neuromuscular system. Neuromuscular efficiency NME is a quantification of excitation-contraction coupling. The altered membrane function across the transverse tubule will affect Ca⁺⁺ release from the sarcoplasmic reticulum: also the amount of Ca⁺⁺ necessary to produce a given tension is greater at lower pH. These inhibitory effects on E-C coupling would account for the reduced NME after sustained fatiguing contractions; hence, more motor units were recruited (compared to pre-fatigue) to generate the same 50% MF. The percent reduction in NME, which varied between subjects as well as in different muscles, was also a measure of the extent of fatigue. The elbow flexors, the most fatigable muscles (mean FI: 48%) had the largest reduction in NME (mean: 49%), and generally the longest recovery times (> 10 min); the ankle dorsiflexors were the least fatigable (mean FI: 34%); had the smallest mean reduction in NME (31%), and the shortest recovery times (1.5min).

EMG augmentation (EMGaug), attributed to synchronization of motor units, (and to conduction velocity decrease) is one of the mechanisms for maintaining force during the initial phase of fatigue. When muscles are used regularly to generate large but submaximal forces, synchronization of motor units increases; conversely, disuse results in a decrease in synchronization. The largest EMGaug recorded from the biceps brachii might be attributed to the regular use of the elbow flexors to generate large forces or it may be an intrinsic property of the muscle; the converse may apply to the first dorsal interosseous, with the lowest mean EMG of 40%.

Effect of weight training on muscle performance: The data presented on the two patients with muscular dystrophy illustrate the use of the foregoing methods in objectively evaluating the effect of a therapeutic modality such as weight training. Discussion of whether exercises are beneficial in the rehabilitation management of neuromuscular disorders will be deferred until completion of the current research project. However, results so far suggest that muscles that are reduced to 20% of normal strength can be strengthened through weight training, if the disease progression is slow, with weight training, weak muscles can sustain maximal workloads without being abnormally fatigued.

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References
The goal is orthofunction, which is defined as the ability to function as mem-
to possess, simultaneously, the attributes of teacher, therapist, and attendant.
cultures that require teaching, rather than primarily medical conditions that
children (unspecified etiology), and adults with multiple sclerosis and Parkin-
son's disease. A basic tenet is that motor disorders are "...learning diffi-
culty that require teaching, rather than ... primarily medical conditions that
require treatment". The teaching is done by "conductors" which are supposed
to possess, simultaneously, the attributes of teacher, therapist, and attendant.
The goal is orthofunction, which is defined as the ability to function as members
of society without assistive devices. Mention is made that the Institute
for the Motor Disordered in Budapest achieves a 70% success rate.

The book is organized into three sections. The first section, "Founda-
tion for the Use of Thermal Agents" is comprised of one chapter on inflam-
mation and repair and a second on pain. Part II, entitled "Instrumentation: Methods
and Applications", has seven chapters and the third part, "Clinical Decision
Making", is comprised of three chapters.

While much of Part I seems unrelated to the title of the text and Part III
limits discussion to the use of heat and cold in athletic injuries and rheuma-
tology, there are two elegant chapters of great value to physical therapists
(both students and practitioners); these being the third chapter on instrumen-
tation considerations, including physics, operating, purchase, and safety, and
chapter 10, "Clinical Evaluation of Thermal Agents."

This text is recommended for both students and graduates of physical ther-
apy as a supplement to more comprehensive texts. (Ernest W. Johnson, MD)