

# REHABILITATION AND MUSCLE TESTING

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## INTRODUCTION

There is a growing need in clinical medicine to validate the quantitative outcomes of an applied therapy. In addition, the measurement of muscle function is an essential component of many neurological and physical exams. Muscle strength is correlated to function, work productivity, and general quality of life. Muscle function becomes compromised: (1) as we age, (2) when associated with a skeletal impairment, and/or (3) as a secondary consequence of many disease processes. Therefore, assessing muscle function is an important clinical skill that is routinely used by neurologists, orthopedists, general practitioners, anesthesiologists, and occupational and physical therapists. Evaluation of muscle strength is used for differential diagnosis, to determine if an impairment or disability is present, to decide if a patient qualifies for treatment, and to track the effectiveness of a treatment.

In a research setting, the measurement of muscle function is used to further our understanding of the normal and potentially impaired neuromuscular system in human and/or animal experiments. In such research, muscle function can be assessed at the intact individual level (*In vivo*), in chronic and acute animal models (*In situ*), within isolated muscle strips or even within single myofibrils (*In vitro*), and/or at the molecular-biochemical level. In this article, only whole muscle testing (*In vivo* and *In situ*) is discussed.

There are several components of muscle performance. The American Physical Therapy Association uses various definitions to explain the characteristics of muscle function (1). Muscle performance is the capacity of a muscle to do work. Muscle strength is the force exerted by a muscle or group of muscles to overcome a resistance in one maximal effort. Instantaneous muscle power is the mechanical power produced by the muscle (muscle force times muscle velocity). Muscle endurance is the ability to contract a muscle repeatedly over time. Of these performance indicators, muscle strength is the one most commonly measured when assessing the muscle function of intact humans.

In assessing muscle strength, the conditions under which the muscle contracts must be specified so that the muscle test data can be interpreted properly. The following conditions are relevant: Isometric contraction: the muscle contracts while at a fixed length; Isotonic contraction: the muscle contracts while working against a fixed load, for example, a hanging weight; Isokinetic contraction: the muscle contracts while moving at a constant velocity; generally, isokinetic contractions are only possible with the limb strapped into a special machine that imposes the constant velocity condition; Eccentric contraction: the muscle contracts against a load that is greater than the force produced by the muscle so that the muscle lengthens while

contracting; and Concentric contraction: the muscle contracts against a load that is less than the force produced by the muscle so that the muscle shortens while contracting.

Isometric muscle tests are the most common as they are the simplest to perform and reproduce and, because the test conditions are well defined, they are the most appropriate for comparing results within a population. Two considerations are important when testing muscle under isometric conditions. First, because muscle force varies with muscle length, the length of the muscle must be specified when planning and reporting a muscle test. The manual muscle test has strict and well-defined rules for the subject's posture and joint positions that must be followed if one is to make clinical decisions based on the test (2).

Second, all isometric muscle tests of intact human muscle are conducted with the limb either held in a fixed position by the examiner, or with the limb fixed to a brace or jig (see the Stimulated Muscle Force Assessment section). While these methods hold the limb in a fixed position, the muscle will not be strictly isometric because of tendon stretch. The mismatch between limb condition and muscle condition only causes problems when trying to infer details about muscle dynamics, such as rise time or contraction speed from externally measured forces. Even if the whole muscle could be fixed at proximal and distal ends, during a twitch, the distance between  $z$  lines in the myofibril will shorten, which means the sarcomeres are shortening due to internal muscle elasticity. This is why the length tension and dynamic properties of whole muscle deviate somewhat from those of the isolated sarcomere. Nevertheless, length tension or ankle-angle/isometric-torque analyses can be done *In vivo* (3,4).

Testing of intact human muscle requires that muscle output be measured external to the body and, as a result, muscle force is never measured directly. As shown in Fig. 1, muscles wrap around joints and attach to limbs at the proximal and distal ends. There is a kinematic relationship between the measured force and the actual muscle force that depends on the details of muscle attachment and varies with joint angle. Therefore, to ultimately solve the kinematic relationship, one will require information about muscle attachment location, the geometry of the joint, and the joint angle. Such geometric information can be readily obtained from an magnetic resonance imaging (MRI) scan or a more generic geometry can be assumed, for example, obtained dimensions gathered from cadaver studies (5,6).

While often reported as a force, external testing of muscles more correctly should be reported as a torque. Figure 2 illustrates how force varies with location of the resistive load along the limb, while torque does not. Reporting muscle strength as torque about a joint eliminates this difficulty. If force is reported, the distance between the joint and the resistive load point should be measured to permit conversion to torque.

External measurement of torque about a limb joint means that all of the forces acting on that joint are measured, and that the contribution of the muscle or muscle group under study cannot be easily separated out. In other words, there are confounding forces generated by synergistic muscles. For example, when testing foot plantar flexion to determine gastrocnemius strength, the soleus



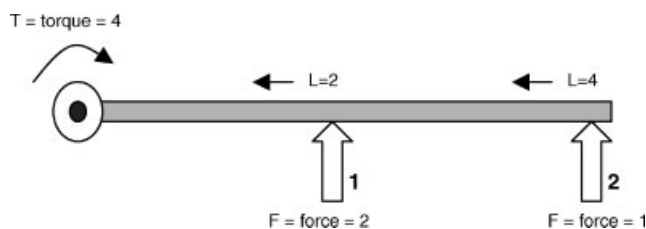
**Figure 1.** Muscles wrap around joints. Muscle force is related to external force produced by a limb through skeletal geometry of joints and attachment points.

may also be contributing to the measured torque about the ankle. Yet, another complicating factor may be undesired activations of antagonist muscles. One example is when you “flex your arm muscles”. In general, the resulting torque from the biceps and triceps are in balance, the arm does not move, and no external torque will be measured even though the muscles are contracting actively.

## MANUAL MUSCLE TEST

The simplest and most common method of assessing muscle strength is the manual muscle test (MMT). Manual muscle testing is a procedure for evaluating strength and function of an individual muscle or a muscle group in which the patient voluntarily contracts the muscle against gravity load or manual resistance (2,7). It is quick, efficient, and easy to learn, however, it requires total cooperation from the patient and learned response levels by the assessor.

The procedures for conducting the MMT have been standardized to assure, as much as possible, that results from the test will be reliable (2,7,8). The specific muscle or muscle group must be determined and the examiner must be aware of, and control for, common substitution patterns



**Figure 2.** A torque of 4 is produced about a joint. It takes an opposing force of 2 to balance the torque if the opposing force is applied at arrow 1. If the opposing force is applied at arrow 2 it only takes a force of 1 to balance the torque. Thus, the perceived torque, and therefore the scoring of muscle strength, depends on where along the limb the examiner places their hand.

where the patient voluntarily or involuntarily uses a different muscle to compensate for a weak muscle being tested.

To conduct a MMT, the patient is positioned in a posture appropriate for the muscle being tested, which generally entails isolating the muscle and positioning so that the muscle works against gravity (Fig. 3). The body part proximal to the joint acted on by the muscle is stabilized. A screening test is performed by asking the patient to move the body part through the full available range of motion (ROM). The main test is then performed either unloaded, against a gravity load, or against manual resistance, and a grade is assigned to indicate muscle strength.

Manual grading of muscle strength is based on palpation or observation of muscle contraction, ability to move the limb through its available ROM against or without gravity, and ability to move the limb through its ROM against manual resistance by the examiner. Manual resistance is applied by the examiner using one hand with the other hand stabilizing the joint. Exact locations for applying resistive force are specified and must be followed exactly to obtain accurate MMT results (2). A slow, repeatable velocity is used to take the limb through its ROM, applying a resistive force just under the force that stops motion. The instructions to the patient are to use all of their strength to move the limb as far as possible against the resistance. For weaker muscles that can move the limb, but not against gravity, the patient is repositioned so that the motion is done in the horizontal plane with no gravity.

Grades are assigned on a 0–5 scale with  $\pm$  modifiers (1 = trace score, 2 = poor, 3 = fair, 4 = good, 5 = normal) (Table 1). Grades  $>1$  demonstrate motion, and grades  $>3$  are against manual resistance. Other comparable scoring scales exist (7).

As noted above, importantly, the assignment of scores is based on clinical judgment and the experience of the examiner. The amount of resistance (moderate, maximal) applied by the examiner is also based on clinical experience and is adjusted to match the muscle being tested as well as the patient’s age, gender and/or body type.

A common alternative to motion-based MMT is the isometric MMT in which the limb is held in a fixed position while the examiner gradually applies an increasing resistance force. The instructions to the patient are, “Don’t let me move you.” The amount of force it takes to “break” the patient is used to assign a score. Scoring norms for isometric MMT are provided in Table 2. While the MMT is the most widely used method to assess muscle function, its reliability and accuracy are questionable (9,10). The MMT scores are least accurate for higher force levels (9,11,12). Interrater reliability for MMT is not high, suggesting that the same examiner should perform multiple tests on one subject or across subjects (2). While not entirely accurate, MMT scores do correlate well with results from handheld dynamometers (13), implying that both are valid measures of muscle strength. However, as explained in a later section, all tests based on voluntary activation of a muscle are prone to artifact because of patient motivation and examiner encouragement.



**Figure 3.** Manual muscle test of the iliopsoas.

**Table 1. Manual Muscle Test Scores<sup>a</sup>**

Score	Description
0	No palpable or observable muscle contraction
1	Palpable or observable contraction, but no motion
1+	Moves limb without gravity loading less than one half available ROM <sup>b</sup>
2–	Moves without gravity loading more than one half ROM <sup>b</sup>
2	Moves without gravity loading over the full ROM <sup>b</sup>
2+	Moves against gravity less than one-half ROM <sup>b</sup>
3–	Moves against gravity greater than one-half ROM <sup>b</sup>
3	Moves against gravity less over the full ROM <sup>b</sup>
3+	Moves against gravity and moderate resistance less than one-half ROM <sup>b</sup>
4–	Moves against gravity and moderate resistance more than one-half ROM <sup>b</sup>
4	Moves against gravity and moderate resistance over the full ROM <sup>b</sup>
5	Moves against gravity and maximal resistance over the full ROM <sup>b</sup>

<sup>a</sup>Adapted from Ref. 2

<sup>b</sup>ROM = range of motion.

## APPARATUS

The appeal of the MMT is that it can be performed simply with the patient, an examiner, and a bench or table. This

**Table 2. Grading of Isometric Manual Muscle Test<sup>a</sup>**

Score	Description
3	Maintains position against gravity
3+	Maintains position against gravity and minimal resistance
4–	Maintains position against gravity and less than moderate resistance
4	Maintains position against gravity and moderate resistance
5	Maintains position against gravity and maximal resistance

<sup>a</sup>Adapted from Ref. 2.

makes it ideal for the routine clinical environment where specialized equipment is unavailable and time is short. It is also suited for situations in which testing must be performed away from the clinic, for example, in nursing homes, rural areas, or remote emergency settings.

When greater accuracy of results is needed, instruments are available that provide precise readouts of the resistive force the muscle works against (14). One example is a handheld dynamometer, such as the one shown in Fig. 4. This instrument is sandwiched between the examiner's hand and the patient's limb, and provides a "readout" of force. The interrater reliability for handheld dynamometers is good when used with a standard procedure (15–17), as is the test-retest reliability (13).

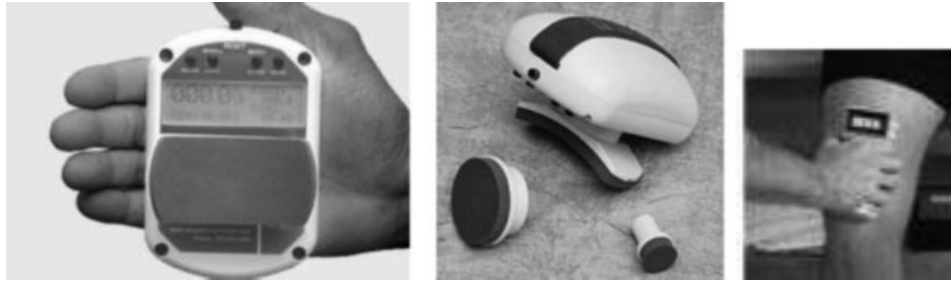
Other products have been developed for specific tests of muscle strength, for example, the hand dynamometer and pinch grip devices shown in Fig. 5. These are easy to use and common for diagnostic tests of the hand. Despite their quantitative nature, readings between different types and brands of dynamometers can vary (18,19).

Computer-controlled dynamometers offer a variety of loading conditions for muscle testing and for strengthening treatments (20,21) (Fig. 6). Along with isometric and isotonic loading, dynamometer machines provide isokinetic conditions in which the muscle group acts against a computer-controlled resistance that moves the limb at a constant angular velocity.

## ADVANCED MUSCLE ASSESSMENT METHODS

### Measuring Muscle Dynamics

Muscle is a complex actuator whose external properties of force and motion result from the action of thousands of muscle fibers which, in turn, result from the action of millions of structural and active proteins whose interaction is triggered by biochemical events. While most muscle testing focuses on the overall strength of a muscle or muscle group, more sophisticated assessment can be useful



**Figure 4.** Handheld dynamometer. Pictured is the Lafayette manual muscle test system from Lafayette instrument company (Lafayette, IN).



**Figure 5.** The Jamar hand dynamometer is pictured on the left (NexGen Ergonomics, Quebec, Canada), and the B & L Pinch Gauge is shown on the right (B & L Engineering, Tustin, CA).

for in-depth examination of muscle function, including its dynamic, kinematic and fatigue properties.

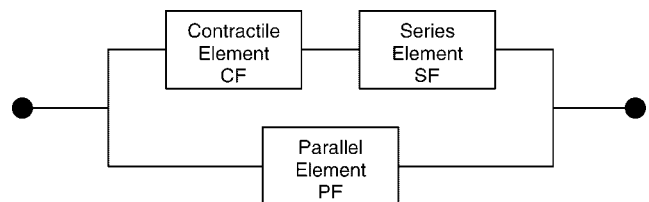
The approach used to measure muscle function in more detail involves developing a mathematical model of muscle activity and then using experiments to identify the parameters of the model. Overviews of these methods are provided in Zajac and Winters (22), Durfee (23), Zahalak (24), Crago (25), and Kearney and Kirsch (26). The modeler

must first choose the appropriate complexity of the mathematical model. The optimum choice is a model that is sufficiently complex to reveal the behavior of interest, but not so complex that parameters cannot be identified. Generally, Hill-type input–output models (27,28) are a good balance, as they capture key force–velocity, force–length, and activation dynamics at a whole muscle level (Fig. 7).

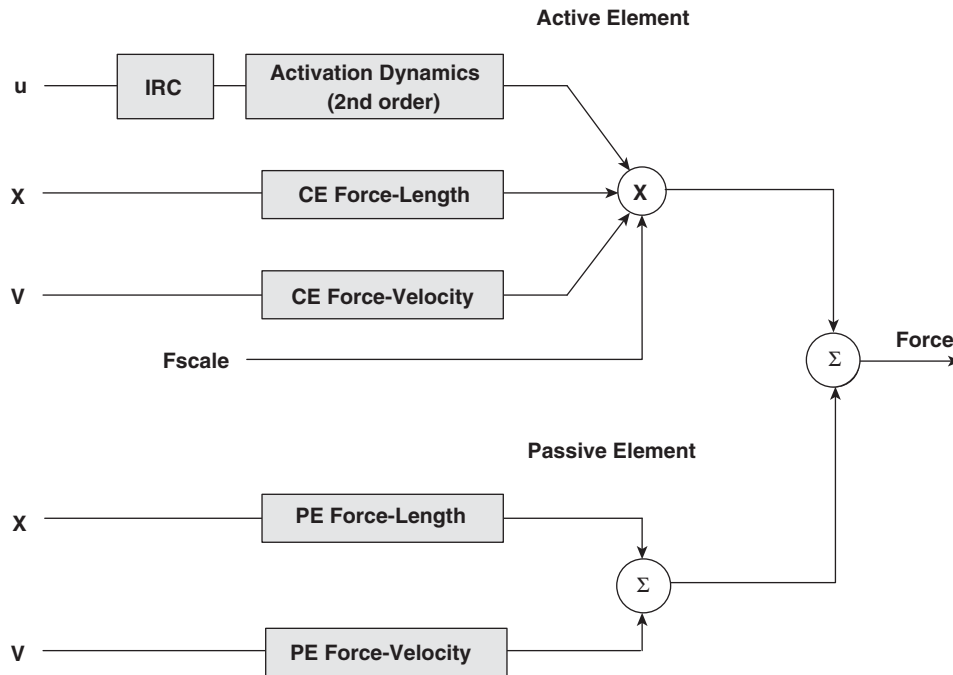
Model parameters can be identified one at a time, using the approach followed by Hill (27), or all at once using modern system identification techniques (23,26). Electrical activation of the muscle is a particularly convenient means for excitation because, unlike voluntary activation, there is control over the input, an essential component for an effective system identification method. Testing can be done



**Figure 6.** Biodex dynamometer for computer-controlled muscle testing (Biodex Medical Systems, Shirley, NY).



**Figure 7.** Hill muscle model. The contractile element (CE) contains the active element with dynamics, force–velocity and force–length properties. The series element (SE) is the inherent internal elastic elements, and the parallel element (PE) represents passive connective tissue.



**Figure 8.** A model that can be used for muscle property identification. The active element has recruitment and twitch dynamics that multiplicatively combine with active force-length and force-velocity properties and sum with passive force-length and force-velocity properties to produce overall muscle force. (For details, see Refs. 23 and 30). IRC = isometric recruitment curve; CE = contractile element; PE = parallel element.

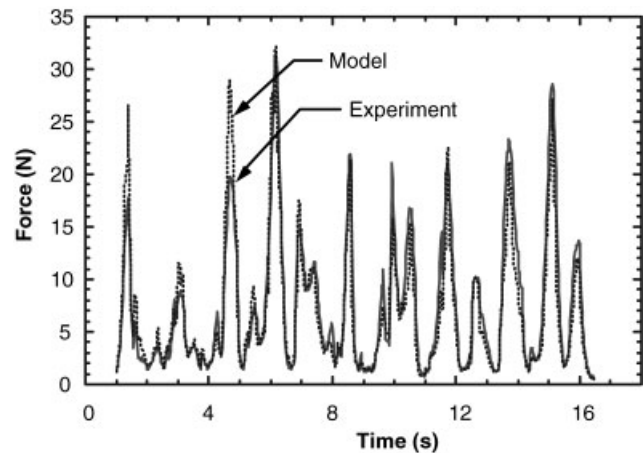
under isometric conditions for determining recruitment and twitch dynamic characteristics, or under arbitrary loading to find active and passive force-length and force-velocity properties.

Identification of muscle properties is most easily accomplished using isolated muscle in acute animal model studies. Here the muscle is unencumbered by joint attachments and extraneous passive tissue. Muscle tendon can be directly attached to a force sensor and placed in a computer-controlled servo mechanism to apply known length and velocity trajectories, all while being stimulated. For example, the isometric recruitment curve, the relationship between muscle force and stimulus strength, can be identified using either point-at-a-time or swept amplitude methods, the latter being efficient in implementation (29). Using the model shown in Fig. 8, active and passive force-length and force-velocity properties can be estimated using brief bouts of controlled, random length perturbations, and then verified through additional trials where both stimulation and length are varied randomly (23,30) (Fig. 9). Simultaneous identification of active and passive muscle properties for intact human muscles is more challenging and represents an ongoing area of research (26).

### Electromyogram

Contracting skeletal muscle emits an electrical signal, the electromyogram (EMG). Electrical recording of the EMG using needle or surface electrodes is an important diagnostic indicator used in clinical neurology to diagnose neuromuscular disorders including peripheral neuropathies,

neuromuscular junction diseases, and muscular dystrophies. The EMG is also used in research as an estimator of muscle activity for biomechanics and motor control experiments. The reader is referred to Merletti and Parker (31) and Basmajian and DeLuca (32) for a comprehensive discussion of surface and needle EMG used in research applications, and to Preston and Shapiro (33), Kimura (34), and Gnatz (35) for an introduction to clinical EMG.



**Figure 9.** Results from an isolated muscle experiment where muscle active and passive properties were identified, then the resulting model was verified against experiment data. Data were generated while the muscle underwent simultaneous, random, computercontrolled stimulation and length perturbations (30).

Nevertheless, this assessment approach requires volitional activation of the patient's musculature under investigation.

### STIMULATED MUSCLE FORCE ASSESSMENT

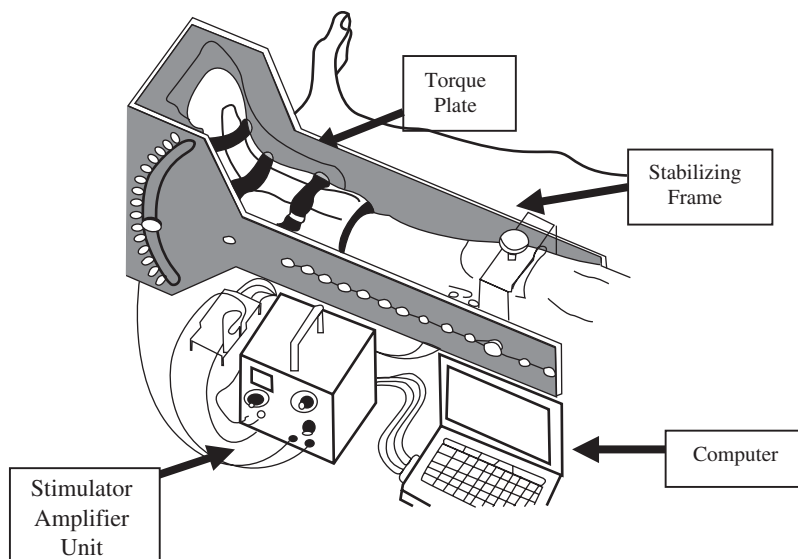
As described above, most devices used clinically to quantify force and increase objectivity still rely on voluntary effort, which can be problematic. Pain, corticospinal tract lesions, systemic illness, and inconsistent motivation can significantly affect voluntarily activated muscle force. In addition, some neurologically impaired patients have difficulty maintaining a constant velocity of limb movement, and some very weak patients are unable to complete a full range of motion in voluntary force assessment tasks (36,37). As a specific example, monitoring muscle function in patients confined to the intensive care unit is a difficult challenge. Often such patients are on potent pain medications (e.g., morphine) and/or are sedated, or may have significant alterations in levels of consciousness due to critical illness (38,39). Thus, it can be extremely difficult to ask such patients to provide reproducible voluntary efforts. Even when cooperation is good, most measures of force assessment are qualitative, similar to using a hand-held unit for testing neuromuscular blockade.

Stimulated muscle force assessment is a versatile approach for quantitative involuntary muscle torque in humans. A muscle is activated by noninvasive nerve or motor point stimulation. A rigid apparatus is used to secure the appropriate portion of the subject's body in a predetermined position that confines movement to a specific direction, for example, ankle dorsiflexion, thumb adduction, arm flexion, or neck flexion (3,4,40,41) (Figs. 10 and 11). The

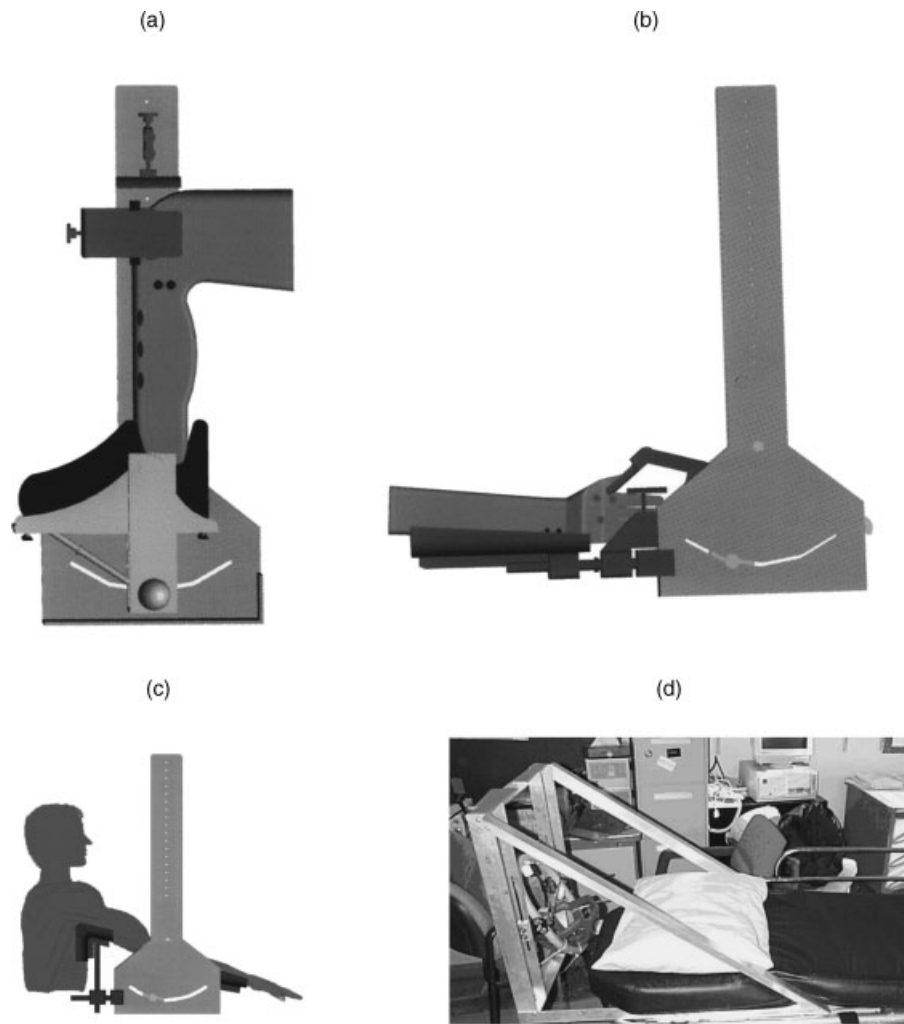
innervating nerves or the motor points of the muscle are stimulated using surface electrodes, with either a single stimulus to generate a twitch contraction or with short trains of stimuli to produce tetanic contractions (e.g., 5 ms interpulse intervals) (3,4). Incorporated strain gauges are used to measure isometric torque and, via acquisition software, all data are immediately displayed and on-line analyses are performed. Various parameters of the obtained isometric contractions are measured, for example, time between stimulus and torque onset, peak rate of torque development, time to peak torque, half-relaxation time, and other observed changes (Fig. 12; Table 3).

Such information is predicted to correlate with underlying physiological conditions and/or the presence of a myopathic or neuropathic disorder. To date, the average torque generated by healthy control subjects varies by < 5% with repeated testing for contractions elicited from the various muscle groups studied (4,40,41). Thus, this assessment approach has potential utility in a number of research arenas, both clinical and nonclinical. Specifically, it has added clinical value in diagnosing a neuromuscular disorder, tracking weakness due to disease progression, and/or quantitatively evaluating the efficacy of a therapy (37,42–45). Compared to current assessment methods, we consider that monitoring isometric muscle torque generated by stimulation improves objectivity, reliability, and quantitative capabilities, and increases the type of patients that can be studied, including those under sedation (39) (Fig. 10). Stimulated muscle force assessment may be of particular utility in studying patients with a known underlying genetic disorder, for it could then provide important information as to genotype–phenotype associations (37).

The general configuration of the measurement system consists of the following main components: a stabilizing



**Figure 10.** Muscle force assessment system to determine involuntary isometric torque of the human dorsiflexor muscles. It is comprised of the following main components: (1) a stabilizing frame with knee supports; (2) the torque plate with mounted boot to fix the foot which can be rotated between  $-40^\circ$  and  $40^\circ$ ; (3) a strain gauge system (Wheatstone bridge circuit) that detects the evoked torque; (4) a stimulator–amplifier unit that can supply variable stimulus pulse amplitudes and pulse durations and can amplify the voltage changes from the Wheatstone bridge circuit; and (5) a computer with data acquisition hardware and software for recording, analyzing and displaying all signals. (Modified from Ref. 39.)



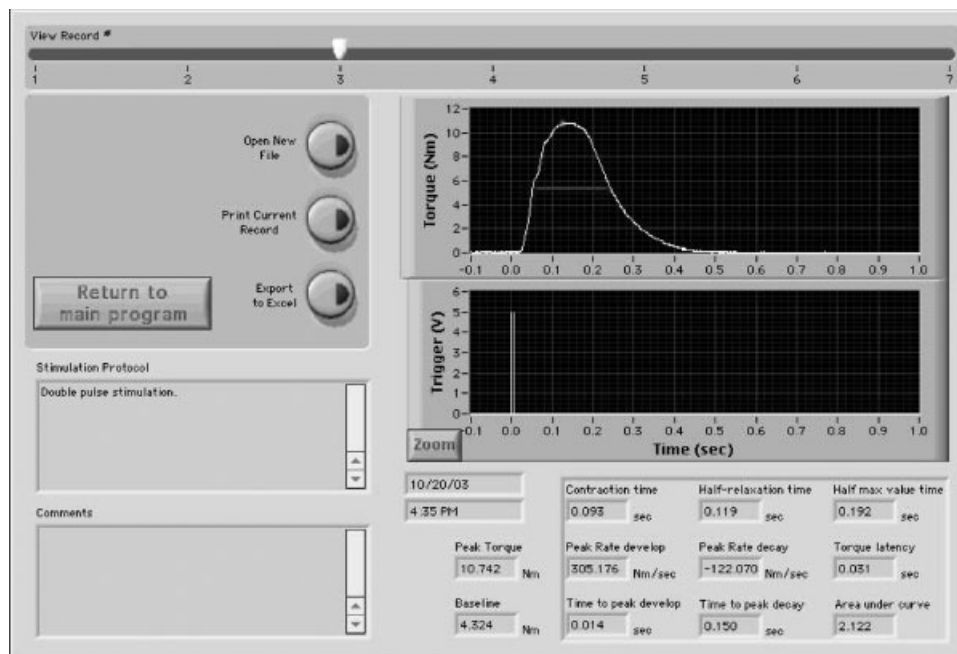
**Figure 11.** Various applications of stimulated muscle force assessment: (a) dorsiflexor muscles in a seated individual with stimulation of the common peroneal nerve lateral to the fibular head; (b) adductor pollicis muscle following ulnar nerve stimulation; (c) activated biceps force with motor point stimulation; and (d) head stabilizing/force system to study sternocleidomastoid muscle function following motor point stimulation. (See also Refs. 4, 40, and 41.)

device that holds either the subject's arm or leg in a defined position; a force transducer that detects the evoked torque produced by a specific muscle group; hardware devices for nerve stimulation, signal amplification, and signal conditioning; a computer for stimulus delivery; and data acquisition software for recording, analyzing, and displaying all signals simultaneously (torque, EMG, applied stimulus) (Figs. 10–12).

The stabilizing device system currently used to study the dorsiflexors is a modification of a previously described apparatus (3). This device can be configured to maintain the subject's leg in a stable position while allowing access for stimulation of the common peroneal nerve lateral to the fibular head (Fig. 11a). The torque about the ankle joint, produced by the dorsiflexor muscles (i.e., primarily generated by the tibialis anterior with contributions from the peroneus tertius and extensor digitorum muscles), is then quantified. One or two padded adjustable clamps can be used to maintain stability of the leg (knee slightly flexed in

a supine position or flexed at 90° while seated). Modified in-line skate boots of varying sizes are affixed to the torque plate and adapted for either the right or left foot. The foot and ankle can be rotated within a 40° range while secured in the skate boot. This device can also be used for subjects in a supine position, in which case the support frame is secured to the upper leg proximal to the knee (Fig. 10) (39,45). To emphasize the extreme versatility of this methodology, note that a specialized version of this device was constructed and used to study dorsiflexor torques in hibernating black bears, *Ursus Americanus*, in the Rocky Mountains (46).

Briefly, the arm and hand stabilizing apparatus, used to measure muscle torque of the adductor pollicis, is easily attached to the main stabilizing frame (Fig. 11b). Using straps, the forearm can be secured to the arm stabilizing unit, which can be adjusted for varying arm lengths. The digits (2–5) are placed in the hand well, and the thumb is secured to the constructed thumb bar attached to the



**Figure 12.** An example of a typical data display available to the investigator during subsequent off-line analyses. Graphically displayed are the muscle torque waveform and the stimulus administered (a double pulse with a 5 ms interpulse interval). Numerically displayed are various contractile parameters. Time 0 is the time of stimulation. The red line indicates the time when half of the peak torque has been generated. The display shown is the torque generated by the dorsiflexor muscles of a normal, healthy subject.

torque plate. Shown in Fig. 11c is the configuration that is used to record force generated by the biceps muscle. As for the aforementioned muscles, force can be produced by peripheral nerve stimulation or by voluntary effort. In addition, we have successfully employed motor point stimulation of the muscle itself with large surface electrodes (40). The forces of the isometric muscle contractions are obtained as changes in torque applied to the instrument torque plate. Finally, we recently reported the optimization of an approach to study forces in the sternocleidomastoid muscle in the anterior neck, and plan to use these methodologies to study the effect of therapy in patients with cervical dystonia.

To date, this assessment approach has been used to study patients with a wide variety of disorders including: amyotrophic lateral sclerosis, Brody's disease, chronic inflammatory demyelinating polyneuropathy, malignant hyperthermia, muscular dystrophy, myotonia, periodic paralysis, and nerve conduction blocks. The new insights to be gained by employing this approach in a variety of healthcare situations will further our clinical insights on the underlying pathophysiologies, and provide us an accurate means to determine clinical outcomes. Recently, we employed this approach to evaluate athletes with potential overtraining syndrome (47), thus the applications for these methodologies could be considered quite limitless.

**Table 3. Contractile Parameters that Can Easily be Quantified**

Parameter	Units <sup>a</sup>	Definition
Peak torque	Nm	Maximum amount of torque developed
Contraction time	Seconds	Time from onset of torque to time of peak torque (e.g., calculated at 90% of peak)
Half-relaxation time	Seconds	Time from peak torque to time when torque decays to half of peak torque
Peak rate of development	Nm/seconds	Maximum rate of torque development
Peak rate of decay	Nm/seconds	Maximum rate of torque decay
Time to peak development	Seconds	Time from onset of torque to the peak rate of development
Time to peak decay	Seconds	Time from peak rate of development to peak rate of decay
Half-maximal duration	Seconds	Time when the generated torque is maintained at a level of half of the peak torque
Latency to onset	Seconds	Time from the stimulus to the onset of torque development

<sup>a</sup>Nm = Newton meters.



## SUMMARY

The assessment of a patient's muscle strength is one of the most important vital functions that is typically monitored. Specifically, strength assessment is necessary for determining distribution of weakness, disease progression, and/or treatment efficacy. The particular assessment approach will be, in part, dictated by the clinical circumstance or severity of illness. Several assessment techniques and tools are currently available to the healthcare provider and/or researcher, yet each has its unique attributes. Nevertheless, as outcomes-based medical practice becomes the norm, the need for quantitative outcomes assessment of muscle strength will become even more important.

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