Techniques to Evaluate Elderly Human Muscle Function: A Physiological Basis

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Elderly persons appear to exhibit muscle weakness and a slowing in their speed of muscle movement. Objective quantification of these characteristics requires reliable and practical tests to assess the muscle contractile characteristics of elderly people. This review discusses the advantages and limitations of voluntary and electrically stimulated muscle testing techniques used to assess the strength, speed, and fatigability of elderly muscle with a brief explanation of the physiological basis. This review presents the practice and theory underlying the scientific measurement of elderly human muscle function, bridging the gap between the practical issues of measurement and the physiological significance of such measurements.

AGING is associated with marked skeletal muscle atrophy and weakness leading to impaired mobility, lack of independence, and increased risk of falls and limb fractures. As the number and proportion of older individuals in developed countries increases, a larger number of clinicians and researchers are becoming involved in developing techniques to evaluate the performance of elderly muscle. Accurate assessment of elderly muscle is important to determine the effects of age on human muscle function in vivo and to quantify the functional adaptations to exercise interventions in elderly persons.

This review will focus on non–task-specific measures that utilize voluntary and electrically evoked contractions to assess objectively the following properties of elderly muscle: the force generating capacity during isometric contraction, speed of muscle contraction and relaxation, maximal dynamic strength, and fatigability. Tests of muscle function using voluntary contractions are reliant on an uncompromised central neural drive to the muscle(s). However, tests of muscle function using electrically evoked (involuntary) contractions are able to assess muscle function independent of the central nervous system. Thus, by using electrical stimulation, factors such as motivation, sense of effort, and central neural drive to the muscle(s) are eliminated during the measurement of elderly muscle function. The purpose of this article is (i) to explain suitable voluntary and involuntary tests and measurements used to evaluate elderly muscle function, and (ii) to discuss the value, limitations, and physiological background of such measurements to aid in the rational choice of appropriate methods for the examination of elderly muscle function.

ISOMETRIC CONTRACTIONS

The process of aging includes a progressive decrease in muscle mass and function that is manifested in a reduced capacity of the elderly person to generate muscle force (1–4). The age-related reduction of strength has been most widely and easily assessed by voluntary isometric contractions. This section will review the measurement of maximal isometric strength in elderly persons and the interpolated twitch technique as a method to assess the ability of elderly individuals to activate their muscle during maximal effort. Further, the controversial issue of whether specific tension (the force generating capacity per unit area of muscle) declines with age is discussed in terms of methodological issues that need to be considered when dealing with the muscle of elderly individuals.

Maximal Voluntary Isometric Strength

Isometric strength begins to decline in limb muscles in men and women between the ages of 30 and 50 years depending on the muscle (5,6). There can also be a large variation in the rate of strength decrement with age between individuals (refer to Figure 1). Studies comparing maximal voluntary contractions (MVC) of different muscles within the same individual indicate that age-related reductions in strength are greatest in the leg muscles (6–8). Clearly, measurement of the strength of a single muscle group cannot be taken as indicative of the status of all muscles of an individual.

Voluntary strength has been most widely tested under isometric conditions because of the comparative ease, safety, and low cost of measuring the voluntary force production of a static limb. The handgrip dynamometer has been the most commonly used device to obtain strength data on large population samples (9–13) and is reported to be accurate, reliable, portable, and easy to administer at low cost (14). However, the handgrip dynamometer has limited functional significance to the mobility, posture, and stability of elderly persons (14). Consequently, strain gauges or commercially available force transducers set within specially designed rigid frames have frequently been used to...
measure other muscle groups that are more functionally significant to the mobility of elderly individuals (15–17). Although force transducers set within frameworks require external calibration, they have been reported to produce reliable, repeatable force records of MVCs in elderly populations (8,15,18,19). Furthermore, these devices can be designed to measure isometric MVCs at various joint angles (20). As maximal force of a muscle group will change with joint angle (21), valid comparisons of the MVCs of muscle groups can only be achieved when each muscle group is assessed at the optimal joint angle for force development. An MVC in which all motor units are optimally activated is indicative of the physiological cross-sectional area (PCSA) of that active muscle (22). However, a true MVC measurement may not always be achieved in the first session of testing. As with younger subjects (23), elderly subjects can show marked improvement in voluntary strength in a time span of less than 1 week (15). This is not due to muscle hypertrophy, but is likely related to initial submaximal muscle activation due to incomplete recruitment or suboptimal firing of the motor units, otherwise called neural insufficiency. To obtain a true MVC, elderly individuals may require a familiarization session prior to testing, particularly those subjects who are unaccustomed to physical activity. Once habituated, the restest measures of MVCs of young and elderly people have been shown to be reliable (15,18,19,24).

Interpolation Technique

To monitor the level of motor unit activation of a muscle during an isometric contraction, an interpolated supramaximal twitch or tetanic stimulus (electrically evoked contraction) can be applied to the muscle during the maximal effort. This technique will determine the degree of central inhibition experienced during voluntary contraction (25,26). During maximal voluntary effort, any rise in force due to the interpolated electrical stimulus, indicates that the elderly subject has not fully and optimally activated all motor units (Figure 2). Interpolated electrical stimulation of a muscle group is advantageous in that a single brief stimulus is well tolerated by elderly individuals. However, several sessions may be required to familiarize elderly subjects with the supramaximal stimulus that is required for this technique. With practice many elderly individuals are able to fully activate all motor units (16,27–29) as do young subjects (26), and under these conditions the contractile machinery of the muscle can be said to be maximally activated.

The interpolated stimulus can be evoked by electrically stimulating the muscle via the motor nerve (e.g., ulnar nerve for the adductor pollicis) or percutaneously over the nerve (30,31). Motor nerve stimulation results in activation of the entire target muscle by using a hand-held probe or through surface electrodes placed on the skin above the nerve. Such stimulation is practical for accessible nerves of the hand and some leg muscles of elderly subjects. Although only a portion of the muscle is stimulated during percutaneous stimulation under isometric conditions, it is a reliable technique (32), providing results that are similar to those achieved with maximal stimulation via the motor nerve (30,31). When percutaneously stimulating the muscle of elderly people, the larger portions of subcutaneous fat compared to young subjects (33–35) may cause a greater resistance to the electrical stimulus, requiring currents/voltages to be higher. No incidence of injury has been reported using this technique with elderly men and women.

Specific Tension

Two reasons may explain the age-associated reduction in strength: (i) a loss of muscle mass (2–4,16,36–38); and (ii) a reduction in the quality of elderly muscle (10,39–45). It is clear that the primary reason for the loss of strength in elderly individuals is muscle atrophy. However, it is unclear whether a reduction in the quality of muscle, i.e., intrinsic muscle weakness, further contributes to a loss of strength with age. To determine the intrinsic strength of muscle requires calculation of specific tension. Specific tension is a
measure of the force generating capacity of a unit of muscle and is calculated as the maximal force per unit of cross-sectional area of muscle (F/CSA: N·cm⁻²).

The resolution of whether intrinsic weakness is apparent in elderly muscle will come only when all methodological issues are addressed. One source of error has been the inability of researchers to ensure maximal activation of elderly muscle during maximal voluntary effort. Incomplete motor unit activation during force measurement will underestimate specific tension. The extent of motor unit activation can be assessed by using the interpolated stimulus technique (16,25,26).

The simplest explanation for the apparent reduction in specific tension of elderly muscle would be an overestimate of the true amount of contractile tissue due to (i) incomplete detection of intramuscular fat, connective tissue, and blood vessels in elderly limbs and/or (ii) an underestimate of the degree of age-related muscle atrophy, particularly if measured at the mid-belly of the muscle (38). To quantify the contractile material of an elderly limb, anatomical cross-sectional area (ACSA) has predominantly been measured. This is estimated from single scans taken at right angles to the longitudinal axis of a limb bone by using imaging techniques. Images are considerably more accurate than anthropometric techniques that will often result in an overestimation in the amount of elderly contractile material in a limb (46-48).

Imaging techniques that have been used to measure the ACSA of young and elderly muscle have included computed tomography (CT) (34,46,47), ultrasound (US) (2,39,49), and magnetic resonance imaging (MRI) (35,38,45). Two facts are now clear from these studies: (i) the amount of contractile material in elderly limbs is less than in the young (34,35,46,47), and (ii) elderly muscle contains greater amounts of intramuscular fat and connective tissue than young muscle (34,35,46,47).

ACSA from a single scan has been typically estimated by (i) planimetric techniques that involve outlining the muscle and subtracting any visible noncontractile material (2,50), (ii) setting an intensity threshold that quantifies only that CSA which is contractile (46,51), or (iii) morphometric techniques using a grid system to identify and count those areas that are muscle, fat, connective tissue, or bone (35). US scans have proved to be a safe and reliable method of quantifying elderly muscle ACSA, allowing a clear delineation of the muscles and their surrounding fasciae (2,39,49). However, accurate alignment of the transducer over the required site may be difficult during measurement (49). CT and MRI scans have the advantage of allowing greater delineation of the intramuscular fat and connective tissue due to their high degree of resolution. MRI is further advantageous in that contractile and noncontractile tissue are determined without exposure of the subject to radiation. Multiple images can be taken safely with MRI, and there is the added flexibility of scanning in more than the axial plane. Furthermore, MRI allows even greater delineation between the tissues, particularly muscle and tendon, that is difficult to distinguish with CT scans (46,47). The high-resolution MRI scans and the possibility of multiple images allow the calculation of muscle volume in elderly limbs (35,45). However, this technique is expensive, and often there is limited access to the required equipment.

Muscle volume is a more accurate measure of the elderly contractile material because ACSA measured from the mid-belly region of the muscle will underestimate the degree of age-associated muscle atrophy (38). In a study using MRI (38), ACSA was measured and muscle volume calculated from multiple scans, together with the strength of the ankle plantar flexors and young and elderly subjects. After detailed analysis of the images, there was no reduction found in specific tension of the plantar flexor muscles of elderly men compared to young men of similar training status. This analysis is the most convincing one yet to indicate that the specific tension of human muscle does not change with age.

However, a more accurate assessment of specific tension requires the expression of muscle force in terms of PCSA. PCSA is the CSA of all muscle fibers taken at right angles to their long axes (52) and takes into account the CSA of fibers in pennate muscles. However, the pennation angle of the muscle fibers that are needed for the calculation of PCSA is difficult to measure. In the calculation of elderly PCSA, the assumption should not be made that fiber pennation angles are similar to those of young muscle because muscle hypertrophy even in young muscle will cause a change in pennation angles (53). PCSA has been estimated using MRI for some young adult limb muscles (54-56); no published data is available for elderly muscle.

Whether elderly muscle is intrinsically weak requires investigation of (i) the myofibrillar packing within elderly muscle fibers, and (ii) the role of the stiffer elderly tendon (57) on the characteristics of the muscle-tendon complex during shortening and lengthening (58). Myofibrillar packing density is measured by quantifying the myofilament spacing within the fiber (59). The myofibril is the basic unit that changes in number to cause fiber and muscle hypertrophy or atrophy (60). Although short-term strength training has failed to show any alterations in myofibrillar density of young muscle (59), a difference in myofibrillar density between young and elderly muscle would change the specific tension, but this has not been investigated in elderly muscle.

Apparent intrinsic weakness evident during shortening (concentric) contractions in elderly individuals is reduced during lengthening (eccentric) contractions (61). Altered cross-bridge mechanics has been favored as one explanation for this phenomenon (62). Another explanation may be found in the increased tendon stiffness of elderly individuals (57,63,64). Tendon stiffness in the elderly may alter the contractile characteristics of the muscle-tendon complex in this group in such a way so as to distort the relationship between stretch velocity and external force generation. A stiffer tendon will transmit more external length change to the muscle fiber during quick stretch or shortening than a more compliant tendon (58). Under such conditions the muscle sarcomere contracts under velocity constraints that differ dramatically from those that are apparent from external measures of joint or limb movement.

**Speed of Contraction and Relaxation**

A marked feature associated with aging is slowing of movement (1). This might simply be a result of muscle
weakness and the nature of the force–velocity relationship of muscle; i.e., greater force production is possible at slower speeds of concentric contraction in young and elderly muscle. If the dynamic force requirement of a muscle is fixed as it often is in life when lifting a finite load (such as bag of sugar or body weight), then to generate this force the weaker elderly muscle is obliged to shorten at a slower speed. However, it is now clear that the elderly muscle is often intrinsically slower during contraction and relaxation than young muscle, and this cannot be explained by weaker force generating capacity or low skill and motivational levels (15,16).

**Twitch Contractions**

Prolongation of twitch time course (contraction and relaxation time) in elderly individuals has been reported for many muscle groups, including the extensor digitorum brevis (65), triceps surae (15,16), tibialis anterior (16), first dorsal interosseous (66), adductor pollicis (67), and thenar muscles (68). Only minor age-associated changes have been shown in the elbow flexors (8,28).

An electrically evoked supramaximal twitch is the result of a near synchronous activation of all the motor units within the muscle. The time course of contraction will be determined by the sum of all the forces developed by these motor units (69), with any prolongation indicating an intrinsically slower muscle. The individual fibers within a muscle will vary in the time course of contraction and relaxation because of differences in their contractile protein composition and kinetics of calcium release and re-uptake (70). Prolongation of twitch time course of elderly muscle could result from increased expression of very slow isoforms of myosin and/or a down-regulation in the kinetics of sarcoplasmic reticulum calcium release and re-uptake. The skeletal muscle of elderly men and women is known to have a relatively larger type I fiber area than that of the young (17,71,72). Furthermore, sarcoplasmic reticulum calcium regulation of skeletal muscle has recently been found to be down-regulated in elderly human vastus lateralis by 37% (17,73), which may explain the prolonged twitch time course that occurs with age.

An isometric twitch contraction is evoked by a single brief supramaximal electrical stimulus delivered to either the motor nerve supplying the target muscle or percutaneously over the muscle. Supramaximal stimulus is achieved by increasing the voltage until the twitch amplitude plausibly over the muscle. Supramaximal stimulus is achieved by increasing the voltage until the twitch amplitude plausibly over the muscle. Supramaximal stimulus is achieved by increasing the voltage until the twitch amplitude plausibly over the muscle. A further increase in voltage of 20% or more will ensure that the voltage is supramaximal (24,74). Other valid protocols accept maximal responses as those that vary by no more than ±5% as stimulus intensity is increased (75).

The contractile properties determined from a supramaximal twitch response that are commonly used to compare young and elderly muscle are as follows: (i) peak force, (ii) time to peak tension (the contraction time) and/or peak rate of force development, and (iii) half relaxation time (taken as the time the muscle takes to relax from peak force to half of its peak force) and/or peak rate of relaxation (15,16,28,65–67). Peak rates of force development and relaxation are calculated by finding the peak differential of force over time (dP/dt and -dP/dt). However because the peak rates of force development and decline are dependent on the height of the twitch (i.e., the peak twitch force will vary depending on the amount of muscle stimulated), these derivatives must be normalized to the twitch peak force so as to convert the data into a rate constant. The rate constant of a muscle is the fixed rate at which a muscle will contract and relax and represents the intrinsic speed of the muscle. This normalization is achieved by dividing the peak rate of contraction or relaxation (represented force/time: N ms⁻¹) by the peak force of the twitch (N ms⁻¹ N⁻¹; i.e., ms⁻²). The contraction and relaxation times that also represent the intrinsic speed of a muscle are not dependent on the peak force of the twitch and are simply represented as units of time (ms). A supramaximal twitch contraction is quite tolerable and achievable for elderly individuals in small and large muscle groups by using percutaneous stimulation. The supramaximal twitch technique provides a measurement of intrinsic speed of muscle contraction and relaxation independent of volitional effort, skill and motivational levels. This is useful because many elderly individuals are unaccustomed to physical activity (76). However, as with all electrically stimulated muscle function tests, limitations exist in that the central command of a muscle that is important in the performance of everyday tasks is isolated from this measurement technique.

Considerable within subject variability will occur in the time course and force of contraction of the twitch response if the conditions of testing are not controlled. The main variables that must be standardized are (i) the intensity (and pulse duration) of the stimulus (77), (ii) muscle length or joint angle (78,79), (iii) immediate activation history of the muscle to avoid posttetanic potentiation and the positive staircase phenomenon (80–84), (iv) muscle temperature (78,85), and (v) muscle fatigue status (36,86). Human studies indicate that under controlled conditions the day-to-day reproducibility of supramaximal twitch properties in young and elderly individuals is reliable (18,19,78).

**Tetanic Contractions**

The intrinsically slower speed of contraction and relaxation of elderly muscle has been determined previously from electrically stimulated tetanic contractions. A tetanic contraction is the result of a rapid succession of electrically evoked twitches that produces a summation of the muscle’s mechanical responses into a fused force plateau. Measurements from tetanic contractions of elderly individuals compared with those of young individuals have demonstrated (i) lower peak rates of contraction and relaxation, and longer relaxation times (15,40), and (ii) a shift to the left in the force frequency curve when normalized as a percentage of the maximum force obtained at the greatest frequency (usually 100 Hz) (15,67).

Rates of contraction and relaxation and relaxation time can be measured from a brief tetanic contraction that has been evoked at submaximal levels of electrical stimulation (17,24,40). A contraction evoked at 30-Hz stimulation frequency is optimal to measure contraction/relaxation rates and times because this frequency will cause a fused contraction (24) without the effects of rapid excitation failure (high frequency fatigue) (87). Maximal rates of contraction
and relaxation of force (dP/dt and –dP/dt) are measured from the steepest parts of the increasing and decreasing force record of the tetanic contraction, respectively. It is important to note that, as for the twitch, these rates (dP/dt and –dP/dt) will be dependent on the height of the tetanic contraction and therefore must be normalized to the peak force developed before comparison between individuals can be made on the basis of the derived rate constants. Once the peak rates are normalized to the peak force of the tetanic contraction (N•ms⁻¹•N⁻¹; i.e., ms⁻¹), this calculation will represent the intrinsic speed of the muscle. The slower rates and times of relaxation from a tetanus observed in elderly muscle compared to that of young muscle are associated with slower uptake of calcium into the sarcoplasmic reticulum and a larger relative type I fiber area (17).

The relaxation time recorded from a tetanus can be measured as the time taken for the muscle to relax from 95% to 50% of contractile force (17,24,40). This measure will usually provide the most reliable relaxation time data in submaximal contractions from percutaneous stimulation that is recommended for elderly subjects. Many force records are contaminated beyond this point in time by a reflex that is evoked by the submaximal stimulus (H-reflex in the triceps surae) (88,89). The H-reflex does not occur with supramaximal stimuli because the antidromic firing of all the motor units blocks its transmission to the muscle. Often contraction time of a tetanus is not measured because of the difficulty in determining exactly when the plateau in the force record has been achieved.

The force of contraction of skeletal muscle evoked at increasing frequencies of stimulation defines a force frequency curve. The slower contracting and relaxing muscle of elderly individuals will result in a leftward shift of the normalized force–frequency curve when compared to that of young individuals (15,67). The mixture of fast and slow twitch fibers within the muscle will have a marked effect on the shape of the force–frequency curve, as the different fibers exhibit different fusion frequencies. A leftward shift of the normalized force–frequency curve indicates an earlier fusion frequency of the elderly muscle due to a prolongation of contraction and relaxation time of elderly muscle.

The recording of a force–frequency curve for young and elderly human muscles can be constructed by creating a graph of the resultant forces of the muscle stimulated at various low and high frequencies using a constant current/voltage intensity. Typically this has been done by using a series of twitches followed by stimulation frequencies of 10, 20, 50, and 100 Hz with 2 s of stimulation at each frequency in a continuous train of stimuli (15,24). As the frequency increases, force is then seen to increase in a stepwise fashion due to the summation of forces (Figure 3). If a constant intensity stimulus is applied to a muscle at these increasing frequencies, then the steepest part of the curve is usually between 1 and 30 Hz (where unfused tetanic contractions are seen), and a force plateau with maximal force production occurs between approximately 50 and 100 Hz when contractions become fully fused (24,90).

The force–frequency relation of the muscle of young and elderly individuals obtained from submaximal tetanic contractions needs to be represented by normalizing all forces to that obtained at a high frequency of stimulation (24). A ratio of the force at a low frequency (e.g., 20 Hz, which is situated on the steep part of the force–frequency curve) to that at a high frequency (50 or 100 Hz on the plateau of the curve) will further summarize the force–frequency relationship. Normalizing the forces to that of a higher frequency is a reliable and reproducible method (15,18,30) that will serve to stabilize the variability of absolute forces obtained during submaximal levels of percutaneous stimulation.

The force–frequency relation will remain constant for most human muscles if the tetanic contractions are greater than 10% of a true MVC (91,92). Submaximal stimulation will provide reliable data and is readily tolerated by elderly subjects. However, in the case of the triceps surae, supramaximal stimulation is recommended because the force frequency relation alters with the intensity of electrical stimulus (75,78). The explanation for this voltage dependency relates to the vastly different proportions of slow and fast fibers in the soleus and two heads of the gastrocnemius of the triceps surae (93,94). Thus, the force–frequency curve will change depending on the intensity of stimulus (voltage/current) and degree of fiber recruitment from each of the individual muscles. To achieve supramaximal levels of stimulation at all frequencies, several sessions of familiarization may be needed with elderly individuals (15). Although supramaximal stimulation may prove uncomfortable at times, these contractions are tolerated by elderly individuals with no injuries reported for supramaximally or submaximally stimulated contractions. Other factors that will alter the force–frequency relation during isometric contraction include the length, temperature, fatigue state, and degree of potentiation of the muscle (90).

**Dynamic Contractions**

There are many reports of poor performance by elderly individuals in simple tests of dynamic performance such as jumping, cycling (95,96), and more common activities of daily living such as stair climbing, walking, and rising from a chair (97–100). Performance of dynamic tasks by elderly

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**Figure 3.** Force–frequency relationship of the quadriceps of a young female (27 years) using submaximal percutaneous stimulation: stimulation for 2 seconds at 10, 20, 50, and 100 Hz. The 100 Hz stimulation is 70% of MVC.
subjects is impaired to a greater extent than would be predicted from measurement of isometric strength alone (96). This section will address the methods and limitations of assessing dynamic voluntary contractions in elderly populations. Furthermore, the electrically evoked dynamic contraction (electrically evoked release method) is discussed as a method to overcome the inability of some elderly individuals to activate their muscle maximally during dynamic contractions.

Maximal Voluntary Dynamic Strength

Maximal voluntary dynamic strength of elderly muscle has commonly been assessed by using (a) the heaviest weight that can be lifted concentrically throughout a complete range of movement (one repetition maximum: 1RM) and/or (b) the maximal torque generated by using an isokinetic dynamometer. A 1RM has commonly been performed in training studies of elderly muscle using a resistance or pin-loaded weights machine that is also used for the training program (17,51,97,101,102). A 1RM task is advantageous in that it is similar to functional tasks such as moving a heavy load through a range of motion (103). This form of dynamic testing in elderly populations has traditionally been considered less safe than isokinetic testing because there is no set control on the speed of movement and often no set range of motion. However, under careful supervision and with appropriate familiarization procedures, a 1RM can be safely conducted (104) even in very frail elderly individuals (97,102). In one study only 2 of 83 elderly men and women (2.4%) were reported to have sustained an injury during 1RM testing (104). Both of the injured subjects were novice trainers, and one of the injuries was related to a previous injury. Another study reported a 19% incidence of injury in elderly subjects who performed a 1RM, but 5 of the 11 injuries (from a total of 57 elderly subjects) were related to preexisting joint problems (105). To reduce the risk of injury some researchers have used a 3RM that requires less absolute load (103). Furthermore, when using a 1RM or 3RM measurement of strength the assessor will need to set an absolute load (103). The mechanisms responsible for these differences are not known and may well be an artifact based on a stiffer tendon of elderly individuals (refer to the section on “Specific Tension”). Furthermore, in testing both eccentric and concentric contractions in any age group, it is always difficult to be certain of the degree of muscle activation when voluntary contractions are used (114).

Maximal voluntary dynamic strength of elderly subjects has predominantly been assessed by performing the standard voluntary isokinetic concentric contraction. The most common measures have been the “peak torque” achieved over a range of movement (3,110,115), or angle specific torques (108,110,115,116) that standardize for the muscle length-tension relationship. If several velocities are assessed, torque-velocity curve can be described (109,110,116). To ensure reliable results it is good practice to perform a practice/familiarization session prior to the testing session to offset any increase in maximal torque generating ability that may occur due to neural insufficiency, randomize the velocities of testing, and allow sufficient rest time between testing velocities to minimize the effects of fatigue.

Peak torques from eccentric contractions of elderly men and women have been measured by using the standard voluntary isokinetic contraction at velocities up to 180°/s (61,111,113). During fast eccentric contractions, large torques in excess of isometric values can be developed by muscle with an associated increased potential for muscle damage and delayed onset of muscle soreness. The increased risk of ultrastructural damage and soreness may be even greater in elderly individuals (117,118), with a larger proportion leading inactive lifestyles and unaccustomed to physical activity (76). However, elderly subjects will require several sessions of familiarization with eccentric contractions to allow reliable and reproducible recordings of these contractions.

There are some limitations to be aware of when assessing the dynamic muscle function of young and elderly subjects with isokinetic dynamometers. First, these large dynamometers are often quite expensive and restricted to the laboratory setting for testing. Second, although the isokinetic dynamometer is able to effectively isolate a muscle group for dynamic performance, as with isometric testing, these movements lack specificity to everyday tasks of elderly individuals (14). The high velocities (300–450°/s) of isokinetic dynamometers are still significantly slower than some voluntary everyday movements of young and elderly individuals. Furthermore, some earlier aging studies using isokinetic dynamometers erroneously reported an initial peak overshoot of torque as peak torque and did not account for the gravitational effect on the limb at various joint angles (14), leading to substantial errors during data analysis (119). Reliable data from these devices can be obtained with careful analysis (120). Despite newer computerized
isokinetic systems now correcting these problems, external calibration and reliability data should be conducted by researchers independent of the manufacturers’ data (14). Finally, some elderly subjects may be unable to achieve maximal torque development at some of the higher velocities of concentric contraction within a short range of movement (110,121). To address this problem, a release technique (sometimes referred to as the “quick release” technique) has been developed that can be used with electrically evoked or voluntary contractions (121,122).

Electrically Evoked and Voluntary Release Technique

To overcome doubts about the level of muscle activation during dynamic contraction, a novel method known as the voluntary release or electrically evoked release technique was first developed (122) and later adapted for use in elderly muscle (121). The release technique involves maximal contraction, initially against a locked dynamometer axle, but after a short isometric phase the limb is released to shorten isokinetically at a preset velocity. Failure of voluntary dynamic activation of the plantar flexors at higher velocities of voluntary contraction (>300°/s) in elderly men was found when the torques obtained by the stimulated release method were compared to the torques obtained from voluntary no-release contractions (109,121).

Using the release technique with supramaximal tetanic stimulation, it was further demonstrated there was a relative reduction in the torque produced by the ankle plantar flexors of elderly men at velocities of 180–300°/s when compared to that of young men (121). The electrically evoked contractions where the entire muscle was activated tetanically indicated that a lower torque at a given velocity was due to altered muscle contractile function in the elderly men. The elderly muscle was required to shorten at velocities that were relatively much further toward the high velocity end of its torque–velocity relationship, indicating the muscle was much slower. This response is related to a lower content of fast myosin isoforms in the gastrocnemius and soleus muscles of the elderly men (123), which is consistent with the loss of fast twitch fiber area in the skeletal muscle of elderly individuals (17,42,124).

The primary advantage of the release technique lies in the ability to ensure maximal force is recorded in movements at high velocity where the natural range of movement is limited. In these instances the time available for generation of force is very short and may impair performance in laboratory testing of muscle function in slower elderly muscles, as found in one study (110). In the case of the triceps surae, voluntary preactivation or stimulation prior to release need only be brief with 400 ms of preactivation sufficient to ensure maximal force production within the limited range of movement (109). Furthermore, a representative torque–velocity curve for an individual could be produced by using stimulation frequencies ranging from 10 to 50 Hz, provided the torque at each speed is normalized to the isometric contraction stimulated at that frequency (109).

To produce a reliable torque–velocity curve, stimulation of the muscle needs to be supramaximal via the motor nerve. It is imperative that the level of muscle activation is held constant throughout the entire muscle contraction and from contraction to contraction in a series of measurements (125). This is difficult to achieve with percutaneous electrically stimulated dynamic contractions involving a large range of movement where movement of electrodes relative to the muscle occurs; e.g., knee extension (126). If maximal percutaneous or motor nerve stimulation cannot be tolerated by elderly subjects, preactivated maximal voluntary concentric contractions via a brief isometric contraction (voluntary release contraction) would be more preferable than submaximal percutaneous stimulation. As yet, the electrical stimulation release technique has not been applied to the study of the torque–velocity relationship of elderly muscle groups other than the triceps surae (109), although the quadriceps of elderly women has been assessed by using the voluntary release technique (108).

Muscle Fatigue

Some daily living tasks require young and elderly persons to perform repeated muscle contractions (e.g., walking up stairs) or static submaximal contractions for an extended period (e.g., holding a heavy bag). If required to perform such tasks at a certain absolute load, a weaker elderly person will fatigue earlier than a younger stronger person because the elderly individual will need to perform the task at a relatively higher percentage of his or her maximal capacity. However, whether elderly muscle fatigues at a greater rate than young muscle at a given relative load is unclear. Studies utilizing electrically evoked contractions to compare the fatigability of the muscle of young and elderly subjects have reported the muscle of the elderly to be either more fatigable (15,127), less fatigable (67), or no different (36,128) to that of young subjects. The reason for the conflicting results is not clear but may be a function of the different protocols stressing different metabolic systems. However, studies using fatigue tests with voluntary contractions are more consistent, indicating that there is little difference in the fatigability of the young and elderly muscle.

Voluntary Tests of Fatigability

Voluntary measures of fatigability have included the following: (i) the relative decline in maximal force of a set number of repeated dynamic contractions performed using an isokinetic dynamometer (120,129), (ii) the relative decline in maximal force of repeated isometric contractions (130), and (iii) the maximal time to maintain a submaximal isometric contraction (129). Despite different muscle groups, velocities, and types of voluntary contraction, elderly muscle has been reported to be no more fatigable than young muscle (120,129–131), with even a possible enhanced resistance to fatigue (129).

Voluntary tests of fatigue are relatively easy to administer in the laboratory setting, although a familiarization session to measure MVC for standardizing the relative force development of contractile work may be required. Similar to analyzing peak concentric torque for maximal dynamic strength, care is required to analyze the peak torque rather than the peak overshoot (14) that may result when performing the standard isokinetic contraction during a fatigue test (120). Although eccentric contractions have been used previously to induce muscle fatigue in the laboratory and con-
trolled setting (117), it is inadvisable to perform fatigue tests using such contractions because of the resultant muscle soreness and time required for elderly muscle to recover (117,118). Voluntary tests of fatigability are able to isolate the site of fatigue to the performance of a particular muscle group, but not whether the site of failure is central (central nervous system) or peripheral (muscle) in origin. Knowing the general site of fatigue can be useful, particularly when assessing elderly patients with neuromuscular disorders.

Electrically Evoked Tests of Fatigability

Attempts have been made to design valid tests of fatigability that exclude the volition and central neural drive to the muscle. An electrically evoked fatigue test that included intermittent contractions (132) has been modified for use on human subjects (75,78). The test involved supramaximally stimulating the human triceps surae muscle group at 20 Hz for 300 ms every second for 2 min and calculating an index of fatigue from the recorded forces (force ratio of the 120th to the 1st contraction). This test was shown to be reproducible in human subjects (with a 7% variability) and unaffected by passive heating of the muscle (78). This protocol is well tolerated by many elderly subjects with some tolerating supramaximal levels of stimulation on a first visit to the laboratory. On the basis of this test it was concluded that elderly muscle was more fatigable than young muscle (15).

However, other studies using electrically evoked contractions with varying protocols and intensities of contraction have concluded that the muscle of elderly men and women (36,67,128). The greatest problem with the evaluation of fatigue resistance in human muscle is the confounding influence of the degree and time of circulatory occlusion produced by the contraction of the muscle under study. Therefore, the extent to which the test stresses aerobic and anaerobic metabolism may differ greatly between subjects or muscles. This may explain many of the contradictory findings regarding fatigue resistance of young and elderly muscle when assessed using electrically evoked contractions and various protocols. The force of contraction required to occlude circulation differs from muscle to muscle in the same individual and between individuals when the same muscle is tested (133,134). Although the literature indicates that in general many of the large postural muscles such as quadriceps and triceps surae suffer circulatory occlusion at 20% MVC (134,135), there is a paucity of evidence to support this conclusion in elderly subjects. It is possible that muscle atrophy associated with old age may increase this threshold to higher relative intensity of contraction in very weak individuals, as is the case in the untrained person who generates a smaller absolute force compared to a stronger weight lifter (136). Furthermore, in fatigue protocols where intermittent short isometric contractions are used (78), the length of time for which circulation is occluded during each duty cycle of contraction and relaxation must also be considered. In slower elderly muscle, occlusion of blood flow will be sustained for a longer period of time than in the faster contracting young muscle because at the end of each contraction, the time taken for force to fall to the threshold for the return of flow will be greater (Figure 4). This may lead to an

![Figure 4](https://academic.oup.com/biomedgerontology/article-abstract/53A/3/B204/540543)

**Figure 4.** The response of a young subject (20 years) and elderly subject (70 years) to the fatigue test of the triceps surae. The test consisted of 120 cycles of electrical stimulation delivering maximal stimuli at 20 Hz for 300 ms repeated once per second for 2 min. The cycle numbers are indicated above the record. Note the pronounced slowing of relaxation and elevation of the baseline in the record of the elderly subject during the last 30 seconds (90-120) of the test. The slowing of relaxation in the elderly subject will lead to an increased time of blood flow occlusion during the fatigue test (Adapted from Davies and White, 1983, ref. 15).
apparent increased fatigability in individuals who have suf-
ered greater restriction in blood flow. This concern
prompted the studies outlined below (137).

In a number of experiments (137) the fatigability of
young and elderly triceps surae were tested by using elec-
trically evoked intermittent contractions (75,78). Tests were
performed with circulation to the lower leg occluded
throughout the test and also under normal conditions.
Elderly men were shown to lose over 50% of the initial
force over the 2-min test (Figure 5) under the control condi-
tion. Fifty percent is a far greater proportion than is lost by
young subjects under the same conditions, and thus elderly
muscle could be said to be more fatigueable than the young
muscle. However, with circulatory occlusion, both the
elderly and young subjects (Figure 5) showed the same
severe fatigue, losing approximately 90% of initial force.
Under these conditions the young muscle was not more
fatigue resistant than the elderly muscle. In a further set of
experiments it was shown that an increase in the length of
the duty cycle (adding a further 300 ms to the rest period
between contractions) caused an improvement in fatigue
resistance in the elderly muscle (Figure 6). Thus, the triceps
surae of elderly men now appeared to be as fatigue resistant
as the muscle of young men when subjected to the same
protocol. This is in accordance with results from voluntary
tests of fatigability. Further, this example illustrates the care
that must be taken to control the test conditions if valid and
objective assessment of elderly muscle function is to be
performed.

CONCLUSIONS
The weaker and slower contractile properties of elderly
muscle can be assessed by using a variety of voluntary and
electrically evoked techniques (Table 1). Reliable tests of
muscle function using voluntary contractions will assess
the integrity of the central and peripheral neuromuscular
system of young and elderly individuals. However, tech-
niques using electrically evoked contractions allow the
muscle of elderly subjects to be assessed independent of
volitional effort and central inhibition, confining any failure
or weakness to the muscle. Comparison of test performances
using a voluntary versus an electrically evoked test
will determine whether the site of failure or weakness is
proximal to the neuromuscular junction and/or within
the muscle. Although motor nerve stimulation may be desire-
able to evoke involuntary contractions, percutaneous stimulation
may be more practical and achievable on the larger muscle
groups when assessing isometric contractile behavior. Reli-
able and reproducible muscle properties can be measured in
the elderly provided time is taken to familiarize them with
the techniques and protocol.

The voluntary and involuntary tests and measures de-
scribed in this review contribute to a larger picture that
pieces together the characteristics and limitations of elderly
muscle function. The challenges for future research are to
(i) investigate and describe a greater range of skeletal mus-
cles in elderly persons; (ii) ensure that the tests of muscle
function are valid and not in reality indirect measures of
other physiological systems; and (iii) link and correlate the

Figure 5. Fatigue tests in the elderly triceps surae of eight men aged
68.5 ± 5.4 years during normal blood flow and occluded blood flow
(ischaemic). Percentage of initial tetanic tension after 30, 60, 90, and 120
seconds of intermittent electrical stimulation delivered as described in
Figure 4.

Figure 6. The effects of changing cycle length on the fatigue index in
two elderly men and one active young adult. The results of six fatigue
tests on each subject are shown. Each test comprised 120 cycles contain-
ing 300 ms of 20 Hz stimulation at a maximal voltage. The cycle lengths
used were 1.0 s (700 ms rest), 1.3 s (1000 ms rest), 2.3 s (2000 ms rest),
3.3 s (3000 ms rest), 4.3 s (4000 ms rest), and 5.3 s (5000 ms rest).
Table 1. Summary of the Relevant Muscle Function Tests Applicable to Elderly Persons

<table>
<thead>
<tr>
<th>Test</th>
<th>Measurement</th>
<th>Purpose</th>
<th>Special Considerations for Elderly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximal voluntary isometric contraction</td>
<td>Peak force of contraction</td>
<td>To determine the maximal strength or force generating capacity of a muscle (group)</td>
<td>Familiarization sessions may be necessary to ensure maximal activation of muscle</td>
</tr>
<tr>
<td>MVC with interpolated electrical stimulus</td>
<td>Height of interpolated electrical stimulus on the MVC</td>
<td>To determine the extent of motor unit activation or central inhibition during voluntary contraction</td>
<td>Familiarization session(s) may be necessary with electrical stimulation; percutaneous or motor nerve stimulation is possible</td>
</tr>
<tr>
<td>Imaging techniques: US, CT, and MRI scans</td>
<td>Cross-sectional area</td>
<td>To quantify the contractile material of a muscle for calculation of specific tension or determination of muscle atrophy of the elderly</td>
<td>One scan may underestimate the degree of whole muscle age-related atrophy; intramuscular non-contractile material needs to be quantified</td>
</tr>
<tr>
<td>Electrically stimulated supramaximal isometric twitch</td>
<td>Contraction and half relaxation times; peak rate of force development; and peak rate of relaxation</td>
<td>To determine the intrinsic contractile speed of muscle</td>
<td>Familiarization sessions may be necessary with electrical stimulation; percutaneous or motor nerve stimulation is acceptable and tolerated by the elderly</td>
</tr>
<tr>
<td>Electrically stimulated isometric tetanic contraction (30 Hz)</td>
<td>Peak rate of force development and peak rate of relaxation; 90–50% relaxation time</td>
<td>To determine the intrinsic contractile speed of muscle</td>
<td>Familiarization sessions necessary with electrical stimulation; submaximal stimulation is acceptable and tolerated by the elderly (the triceps surae needs to be maximally stimulated)</td>
</tr>
<tr>
<td>Electrically stimulated contractions at increasing frequencies (10, 20, 50, 100 Hz)</td>
<td>Force–frequency curve or low: high frequency ratio (20/50 Hz)</td>
<td>To determine the intrinsic contractile speed of muscle; a shift left in the force frequency curve or a higher ratio indicates a lower fusion frequency of elderly muscle</td>
<td>Familiarization sessions necessary with electrical stimulation; submaximal stimulation is acceptable and tolerated by the elderly (the triceps surae needs to be maximally stimulated)</td>
</tr>
<tr>
<td>Maximal dynamic strength with a fixed load</td>
<td>One or three repetition maximum (1RM, 3RM)</td>
<td>To determine the maximal load that can be lifted concentrically through a range of movement</td>
<td>Training and supervision required for this technique so as to lift at a relatively constant speed; an objective range of movement needs to be set for the criteria of a successful lift; variable resistance weights equipment is preferable</td>
</tr>
<tr>
<td>Maximal voluntary isokinetic contractions</td>
<td>Peak torque, angle specific torque–velocity curve</td>
<td>To determine the maximal dynamic strength of a muscle (group) during shortening and/or lengthening at a set speed</td>
<td>Several practice and familiarization sessions may be required for concentric and definitely eccentric contractions; avoid high velocity maximal eccentric contractions due to an increased risk of muscle damage in the elderly; elderly may not be able to achieve full activation at high velocities during a limited range of movement; eccentric contractions in the elderly may be influenced by a greater tendon stiffness in the elderly</td>
</tr>
<tr>
<td>Maximal voluntary isokinetic release contraction</td>
<td>Angle specific torque; torque–velocity curve</td>
<td>To determine the maximal voluntary dynamic strength of the muscle (group) at specific joint angles during shortening and/or lengthening at a set speed</td>
<td>Maximal activation of elderly subjects is possible due to the isometric preactivation; several practice and familiarization sessions will be required for maximal concentric and definitely eccentric contractions; avoid high velocity maximal eccentric contractions due to an increased risk of muscle damage in the elderly; eccentric contractions in the elderly may be influenced by a greater tendon stiffness in the elderly</td>
</tr>
<tr>
<td>Electrically stimulated release technique</td>
<td>Angle specific torque; torque–velocity curve</td>
<td>To determine the maximal dynamic torque generating capacity of a muscle (group) during shortening at a set speed without central inhibition</td>
<td>Familiarization sessions necessary with electrical stimulation; testing will be limited to smaller muscle groups due to discomfort of maximal stimulation that is required for this technique; maximal activation of contractile material is ensured in elderly subjects</td>
</tr>
<tr>
<td>Voluntary fatigue tests</td>
<td>Fatigability; ratio of first: last contraction; time to maintain an isometric MVC or submaximal contraction</td>
<td>To determine the fatigability of the neuromuscular system</td>
<td>Familiarization sessions will be required with maximal voluntary contractions; avoid eccentric contractions in the elderly</td>
</tr>
<tr>
<td>Electrically stimulated 2-min fatigue test at 20 Hz</td>
<td>Fatigability; ratio of the first contraction: last contraction</td>
<td>To determine the fatigability of the contractile material (muscle)</td>
<td>Familiarization sessions will be necessary with electrical stimulation; submaximal stimulation is acceptable in all muscle groups; percutaneous or motor nerve stimulation is acceptable; avoid constant circulatory occlusion in the elderly by using a long duty cycle</td>
</tr>
</tbody>
</table>
very task specific tests of muscle function with the non–task-specific techniques as described in this review.

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