Muscle Mechanography

A Novel Method to Measure Muscle Function in Older Adults

Murad H. Taani, MPH, RN; Christine R. Kovach, PhD, RN, FAAN, FGSA; and Bjoern Buehring, MD

ABSTRACT

Muscle function decline is a commonly observed process that occurs with aging. Low muscle function, an essential component of sarcopenia, is associated with negative outcomes, including falls, fractures, and dependency. Although many tools have been developed and are used to assess muscle function in older adults, most have important limitations. Muscle mechanography is a novel method that can quantitatively assess muscle function by performing movements such as heel raises, chair rises, or jumps on a ground reaction force plate. It can also assess balance by measuring sway of the center of pressure. Muscle mechanography promises to have advantages over currently used tools, appears to have better reproducibility, and can assess a broader range of physical function—from master athletes to frail individuals. Older adults can safely perform muscle mechanography measurements. Further research is needed to determine whether muscle mechanography can predict outcomes such as falls, fractures, and mortality.

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Assessing muscle function in older adults has become an important topic in the field of geriatric research. Aging is associated with changes in body composition and functional capability, including a reduction in muscle mass and muscle function (Morley, 2012). These age-related reductions have been named *sarcopenia* (Fielding et al., 2011). Recent estimates indicate that up to 45% of older adults in the United States experience sarcopenia, depending on which population is studied and which definition is used (Janssen, Shepard, Katzmarzyk, & Roubenoff, 2003). Older adults with sarcopenia are at greater risk for falls, fractures, and head injuries (Buehring, Krueger, & Binkley, 2010; Morley, 2012). Compromised muscle function in older adults was found to be an independent predictor of

Mr. Taani is Research Associate, and Dr. Kovach is Jewish Home and Care Center Research Professor in Aging, College of Nursing, University of Wisconsin–Milwaukee, Milwaukee; and Dr. Buehring is Assistant Professor of Medicine, Division of Geriatrics and Gerontology/Osteoporosis Clinical Research Program, University of Wisconsin–Madison, Madison, Wisconsin.

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Address correspondence to Murad H. Taani, MPH, RN, Research Associate, College of Nursing, University of Wisconsin–Milwaukee, 1921 East Hartford Avenue, Milwaukee, WI 53211; e-mail: mhtaani@uwm.edu.

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increased use of long-term care facilities, hospitalization, disability, and mortality (Clark & Manini, 2010; Hirani et al., 2015; Landi et al., 2013).

Assessment of sarcopenia requires measurement of muscle function. Key physical units necessary to quantify muscle function include: force (Newtons [N]), velocity (m/s), and power (watts [W]). Muscle force relates to the force exerted to get the body moving, or the direct muscle forces imparted to the skeleton during movement. Common tests assessing muscle force are grip strength or knee extensor strength. These tests require a maximal muscle contraction to create a peak force. Muscle force is one of the primary regulators of bone mass and an important determinant of bone and joint health in older adults. Muscle force is strongly correlated with bone strength, bone size, total bone area, and femoral neck bone mineral density (Hardcastle et al., 2014; Pojednic et al., 2012; Rantalainen et al., 2009; Runge & Hunter, 2006). Muscle velocity (or movement velocity) is the rate of motion (speed) in a specific direction. The best example of a test measuring velocity is the 4-m walk to assess gait speed. Velocity (e.g., gait speed) slows with aging and is a key component in the onset of functional impairments in older adults.

Muscle force and velocity are significant determinates of power production and functional task performance in older adults (Pojednic et al., 2012). *Muscle power* is defined as the ability to generate as much force as possible and as quickly as possible. It is calculated as the product of force and velocity. Thus, altered neural or muscular ability affecting either factor (force or velocity) will contribute to declines in power and potentially physical function (Pojednic et al., 2012). Examples of tests measuring power are the chair-rise test and countermovement jumps. Muscle power is a valuable measure for identifying age-related physical impairments and strongly correlates with physical capability, mobility, the risk of falling, and sarcopenia (Caserotti, Aagaard, Simonsen, & Puggaard, 2001; Runge & Hunter, 2006; Runge, Rittweger, Russo, Schiessl, & Felsenberg, 2004; Siglinsky et al., 2015; Singh et al., 2014). Leg power is often corrected for body weight (W/kg).

Several traditional muscle function measures have been developed, validated, and used to assess muscle function in older adults (Siglinsky et al., 2015). Among these, gait speed is one of the most frequently used methods. It is measured as the time taken to walk 4 m or another distance achieved during a 2-minute timeframe. Gait speed is a predictor for falls, fractures, hospitalization, caregiver need, and mortality among older adults (Montero-Odasso et al., 2005; Studenski et al., 2011). The chair-rise test is measured by the time required to rise from a chair five times without using its arms. After first assessing if the individual is able to rise once successfully, he/she will be asked to rise from a chair five times and time to complete the five chair rises will be recorded. Repeated chair-rise performance is strongly related to fall and hip fracture risk among older adults (Cawthon et al., 2008). The grip strength test assesses muscle strength using a hand-grip dynamometer. Grip strength is associated with important clinical measures, including disability, length of hospital stay, postoperative complications, and mortality in older adults (Bohannon, 2015). Low grip strength is also associated with various causes of death, including myocardial infarction, stroke, fall, and fracture (Leong et al., 2015).

However, many of the traditional tests have limitations: they often cannot be used over a wide range of performance levels and have drawbacks for testing older adults who have very high or low functional ability. For example, self-selected usual gait speed has a ceiling effect because at some point the individual is walking at a faster pace than his/her usual pace or even jogging/running. The chair-rise test has a floor effect because individuals who cannot rise from the chair cannot be measured. Often these measures only examine particular aspects of muscle function (e.g., balance, power, force) and few provide a quantitative measure (e.g., force, velocity, power). For example, the traditional chair-rise test requires maximal power (W) but is reported in seconds (Buehring et al., 2013; Puthoff, 2008; Siglinsky et al., 2015). Other limitations of these tests include dichotomous (pass/fail) determinations and being prone to human errors as the final results depend on the times taken by individual examiners (Buehring et al., 2013; Siglinsky et al., 2015).

Therefore, quantitative methods for the precise measurement of muscle function in older adults over a broad range of performance is desirable. The National Institute of Nursing Research (NINR; 2011) has emphasized extending nursing science through the integration of biological sciences and supporting and employing new innovative technologies for research questions and methods. These technologies should include methods to optimally assess muscle function in older adults. Muscle mechanography is an innovative technology that quantitatively assesses muscle function parameters in older adults using a ground reaction force platform (GRFP). The purpose of the current article is to introduce muscle mechanography as a method to assess muscle function in older adults. The review covers the mechanism of muscle mechanography, different types of tests, parameters that can be obtained by

TABLE

Operational Definitions of the Variables Available Through Muscle Mechanography

Variable	Definition
Force	The total force exerted on the platform to get the body moving, which also causes acceleration. Force is exerted by movements. Force is calculated by multiplying the body's mass with its acceleration. Force (Newton) = mass (kg) x acceleration (m/s).
Velocity	Velocity is the rate of motion (speed) in a specific direction. It is calculated by integrating acceleration over time.
Power	Power is a necessary parameter to measure movement. Movement is the action of force along a specific distance in a certain time, which is measured as power. Power is also used to describe the rate at which energy is used. It is calculated by multiplying force and velocity. Power = force x distance/time = force (N) x velocity (m/s).
Esslinger Fitness Index (EFI)	This is the performance of movement. The EFI represents the maximum jump power relative to body weight for one's age (ages 3 to 99 years) and gender-matched reference population.
Jump height	Jump height is defined as the displacement of the body's center of gravity. Integration of velocity over time results in displacement of center of gravity/jump height.

using muscle mechanography, measurement procedures, reproducibility, and safety.

MUSCLE MECHANOGRAPHY

Muscle mechanography can quantitatively assess muscle function (force, velocity, power, center of gravity/sway) using a GRFP. Movements that can be measured include heel rise, chair rise, hopping, jumping, and static balance positions (e.g., semi-tandem or tandem stance). A variety of GRFP systems have been used in research settings (Buehring et al., 2010; Matheson et al., 2013; Rantalainen et al., 2010; Rittweger, Schiessl, Felsenberg, & Runge, 2003; Singh et al., 2014). One of the most commonly used systems is the Leonardo Mechanograph®.

Principle of Measurement

The Leonardo Mechanograph GRFP comprises two symmetrical left- and right-sided force plates, which measure and quantify any asymmetries in individuals' physiological movements. A mass (e.g., body weight) creates a vertical ground reaction force on the plates, which elicits changes in electrical resistance in the GRFP's sensors that are proportional to the exerted force. The voltage changes are measured at a frequency of 800 Hz by four strain gauge force detectors located in each force plate (eight total force sensors). The collected voltage reading is transferred via a USB 2.0 connection to a personal computer running the Leonardo Mechanography software (Binkley & Specker, 2008; Matheson et al., 2013; Rittweger et al., 2003; Veilleux & Rauch, 2010). From the measured voltage and changes in voltage over time, the software can calculate other muscle function parameters, such as velocity and power. Several software versions are available and the most recent includes reference data for individuals ages 3 to 99 years.

Muscle Function Parameters Obtained Using Muscle Mechanography

Unlike traditional muscle function tests, muscle mechanography directly measures the applied force vector and calculates measures of force, velocity, power, jump height, and sway (i.e., the change of the center of gravity during a balance test) (Buehring et al., 2010; Matheson et al., 2013; Rittweger et al., 2003). The Leonardo system also reports the Esslinger Fitness Index, an age- and sex-adjusted measure of power assessed during countermovement jumps. Operational definitions of the variables available through Leonardo mechanography are presented in the **Table**.

MEASUREMENT PROCEDURES

Platform Quality Assurance

Although no standardized procedure exists, it is the current authors' recommendation that the platform should be calibrated at least weekly to assure accuracy and precision of the static properties before performing any tests. In addition, it should be calibrated every time it is moved from one location to another. Three 20-kg Troemner cast iron grip handle weights were used for calibration in the current authors' studies. These weights are stacked in one corner of the platform and the measurement of the weight is recorded. This process is repeated for each of the other

Figure 1. Example of older adult participant performing a countermovement jump under supervision of two trained staff members.

three corners. In addition, two weights are placed side by side in the middle of the platform with a third weight placed on top to obtain a central measurement. If any measurements are outside of the ±0.5-kg limit, recalibration is needed.

Test Procedures

Several tests and movements can be performed on the GRFP. All tests are generally easy to understand as they are natural movements that most individuals have performed throughout their lives (e.g., rising on the toes, rising from a chair, hopping/jumping). However, it is recommended that participants receive standardized instructions and that the tests be demonstrated by a trained staff member. In addition, older adults should wear a gait belt while performing tests and at least two staff members should be present to ensure the individual's safety. Staff should be ready to assist the participant who is wearing a gait belt in case he/she loses balance (**Figure 1**).

Heel-Rise Test. The main outcomes of this test are velocity and power. The test comprises heel rises with the goal of achieving the maximum speed of their upward movement. After standing still on the force platform, participants should be instructed to rise on their tiptoes by lifting their heels from the force platform as quickly as possible after hearing a single-tone beep (Veilleux & Rauch, 2010). A double-audible tone indicates the end of the test. Participants are asked to perform three heel raises and the heel raise with the greatest height is used for analysis. This test is useful for older adults who have a degree of functional disability that limits their ability to participate in the jump and chair-rise tests.

Chair-Rise Test. The major outcomes of this test are force, velocity, and power. In addition, this test evaluates a movement that is highly relevant in everyday life (Veilleux & Rauch, 2010). A specific bench is installed on the force plate for the purpose of this test. After sitting on the bench with feet on the ground, participants are instructed to cross their arms over their chest, then stand up straight and sit down again as fast as possible. If participants rise successfully, they are instructed to repeat this five times as quickly as possible. These are exactly the same instructions as for the traditional chair-rise test, but muscle power is reported instead of time. The rise with the highest maximum power, or an average of several rises (three to five), is analyzed.

Single Two-Legged Countermovement Jump. This test has been extensively used among older adults in research settings (Buehring et al., 2010; Matheson et al., 2013; Rittweger et al., 2003; Runge et al., 2004; Siglinsky et al., 2015; Singh et al., 2014). The main outcome of this test is power (usually body weight corrected power [W/kg] is reported), but velocity and force can also be examined. To perform the test, participants stand on a platform, with a foot on each side, as still as possible. After standing still on the platform for at least 2 seconds, participants' body weight is recorded. Participants should be instructed to perform the jump as quickly and as high as possible, using both legs after hearing a single-tone beep. Participants should stand up straight and remain still after landing on the platform for at least 2 seconds until a double-tone beep indicates the end of the test (Buehring et al., 2010; Veilleux & Rauch, 2010). Participants can jump freely, without any arm movement restrictions (**Figure 2**). This procedure is repeated several times, with the goal to get three countermovement jumps deemed valid by the software. Participants should be given time to rest and recover between jumps. Depending on the participant's ability to lift off the platform completely and stand still before and after the jump, it might not always be possible to record three valid jumps. The jump with the greatest height is selected for analysis.

Serial One- or Two-Legged Jumps (Hopping). Although this type of test measures force, velocity, and power, it is used to assess maximal jump force, which is correlated with bone strength, bone size, bone strength indices, total

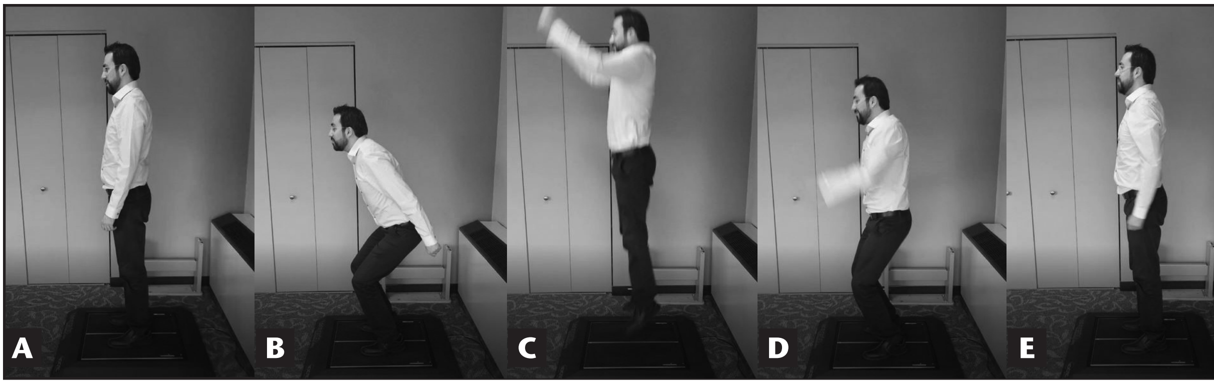

Figure 2. Sequence of a countermovement jump: (A) before the jump, the participant stands in an upright position on the force platform as still as possible; (B) the participant squats as quickly as possible before the jump; (C) the participant jumps as high as possible; (D) the participant begins the smooth landing stage; and (E) the participant stands up straight and as still as possible.

bone area, and tibial strength strain index (Hardcastle et al., 2014; Rantalainen et al., 2009; Runge & Hunter, 2006). Participants are instructed to hop on one forefoot or both forefeet with their knee almost straight and without touching the ground with their heel. Participants should hop 10 times. The software detects and eliminates hops if heels hit the ground; the hop with the highest force is used for analysis (Veilleux & Rauch, 2010).

Balance Assessment/Measurement of Sway. This test can be used to assess balance, coordination, and fall-risk assessment in older adults. Participants try to stand as still as possible in a comfortable upright position with both arms hanging free and a foot on each side of the platform for a specific period of time (e.g., 10 seconds). Various feet positions and open or closed eyes, such as used by the Romberg, semi-tandem, and tandem stands, can be chosen to increase difficulty. Instructions for these foot positions are identical to the ones used in validated test batteries, such as the short physical performance battery (Guralnik et al., 1994). During these tests, the position of the center of pressure (COP) on the platform is recorded. In addition to the traditional scoring of these balance tests, outcome parameters (e.g., total COP path length [m], sway area [m^2], mean velocity [m/s]) can be measured. These parameters can be used to describe the direction and extent of postural sway. The smaller the COP path length or sway area, the better the stability. The velocity (i.e., COP path length divided by trial duration) represents the amount of activity required to maintain stability; the smaller the COP velocity, the better the postural control (Treffel et al., 2016).

SAFETY OF MUSCLE MECHANOGRAPHY

Muscle mechanography has been used in many research studies across various populations, including young and older adults (Buehring et al., 2015; Dietzel, Felsenberg, & Armbrecht, 2015; Hardcastle et al., 2014; Matheson et al., 2013; Rittweger et al., 2003; Runge et al., 2004; Siglinsky et al., 2015; Singh et al., 2014), athletes (including master athletes) (Ireland et al., 2015; Michaelis et al., 2008), as well as children and adolescents (Binkley & Specker, 2008; Fricke, Weidler, Tutlewski, & Schoenau, 2006; Veilleux & Rauch, 2010). None of these studies reported pain, falls, or fractures while using muscle mechanography. Furthermore, in the current authors' unpublished data of more than 300 older adults, all participants were able to complete most tests on the platform (<5% were not able to perform countermovement jumps). Mild joint pain was the only complaint, but there were no lasting adverse events.

Buehring et al. (2015) conducted a study to examine the safety of jumping mechanography (using countermovement jumps) in an older population including individuals with osteoporosis and prior vertebral fracture. Jumping mechanography was determined to be a safe and useful method. Self-reported pain did not change after countermovement jumps and no injuries or new vertebral fractures were sustained, even in individuals with low bone mass density and previous vertebral fractures (Buehring et al., 2015). Individuals older than 90 with moderate control of balance, who were unable to perform the repeated chair-rise test, were able to complete other tests, including countermovement jumps, without any complaints or adverse events (Rittweger et al., 2003). Very frail individuals may ask for more assistance to complete countermovement jumps and some may only be able to perform heel rises. Evidence supports the safety of muscle mechanography in older adults.

REPRODUCIBILITY OF MUSCLE MECHANOGRAPHY

The reproducibility of muscle mechanography has been examined in several studies (Fricke et al., 2006; Matheson et al., 2013; Rittweger et al., 2003; Veilleux & Rauch, 2010). Buehring et al. (2015) have recently found that jumping mechanography (i.e., using countermovement jumps) has excellent test–retest reliability compared to other traditional muscle function tests in 97 adults age 70 and older. Jumping mechanography and grip strength had the highest intraclass correlation coefficients (ICC) (0.93 and 0.95, respectively), whereas traditional chair rises and gait speeds had lower ICCs (0.81 and 0.76, respectively).

Other literature supports the finding that jumping mechanography and gait speed perform better than Timed Up and Go, 10-m gait speed, and chair-rise tests (Rittweger et al., 2003). Jumping mechanography has good test–retest reliability, with low intra-subject, short-term error (3.6%); large inter-subject coefficient of variation (45.4%); and a high test–retest correlation coefficient ($r = 0.99$) (Rittweger et al., 2003). Good reproducibility results of muscle mechanography are further supported in samples of children and middle-aged adults (Matheson et al., 2013; Veilleux & Rauch, 2010). Interrater coefficients of variation were <0.6% for the two-leg countermovement jumps and intrarater coefficients of variation were <5.3% for all variables (Matheson et al., 2013). Veilleux and Rauch (2010) reported coefficients of variation ranged from 3.4% to 7.5% for multiple one- and two-legged jumps, single two-legged jumps, and heel-rise tests.

Muscle mechanography is a method that has well-documented reliability, reproducibility, and promises to be a sensitive test to detect even small functional changes in older adults. In addition, it has less test variability than other traditional muscle function tests (e.g., gait speed, chair rise).

IMPLEMENTING MUSCLE MECHANOGRAPHY IN NURSING RESEARCH

Most nursing research studies involve the collection of data through traditional methods, such as self-reporting or observation tools. Using innovative and advanced methodology in nursing research is highly recommended (NINR, 2011). A growing body of evidence indicates that identifying muscle power, with specific attention to the contribution of force and velocity, is a critical component in the design of intervention strategies aimed at ameliorating muscle function and physical ability in older adults (Pojednic et al., 2012). Muscle mechanography provides in-depth knowledge of the individual contributions of force and velocity to muscle power so interventions can be tailored to optimize the most influential component. Muscle mechanography can also be used to evaluate the potential of nursing therapeutic interventions in older adults (Caserotti et al., 2001; Dietzel et al., 2015; Rantalainen et al., 2010; Runge et al., 2004; Singh et al., 2014; Tsubaki et al., 2016).

The current review highlights potential advantages of muscle mechanography, including (a) that it is computerized (making it less prone to human error and variation), (b) being able to report actual physical units of interest for particular tests, (c) assessing a wide range of physical ability (less ceiling or floor effects), and (d) that it is reproducible and safe in older adults. Muscle mechanography can assist nursing researchers toward building a comprehensive picture of the muscle function in older adults, predicting the onset of physical decline, and identifying the changes in muscle function parameters potentially more precisely than traditional methods (Buehring et al., 2015; Fricke et al., 2006; Matheson et al., 2013; Pojednic et al., 2012; Rittweger et al., 2003; Veilleux & Rauch, 2010). Because of these advantages, muscle mechanography has the potential to reduce the sample size, duration, and total cost of research studies.

Despite all these advantages, muscle mechanography has some limitations. First, although the method can be performed by most older adults, some may be unable to perform some tests due to severe frailty or significant physical impairments. However, even very frail older adults can perform at least one or two of the available tests. Second, studies are lacking to determine whether muscle mechanography results can be used to predict outcomes such as fractures, hospitalizations, and mortality. As researchers become familiar with muscle mechanography and begin incorporating this technology into more studies, data will be available to fill gaps in evidence. Muscle mechanography correlates well with measures of maximal force, such as grip strength and muscle mass, and also traditional muscle tests (Siglinsky et al., 2015). Many studies show that these muscle function parameters are associated with health outcomes among older adults. For example, muscle force correlates with bone health in older adults (Hardcastle et al., 2014; Rantalainen et al., 2009), and muscle power correlates with age (Buehring et al., 2010; Rantalainen et al., 2010; Runge et al., 2004), fall risk (Caserotti et al., 2001; Runge & Hunter, 2006; Runge et al., 2004), impaired physical performance and activities of daily living (Caserotti et al., 2001; Dietzel et al., 2015; Runge et al., 2004; Tsubaki et al., 2015), and sarcopenia (Siglinsky et al., 2015; Singh et al., 2014). As such, although no direct evidence exists that muscle mechanography can predict health outcomes, the correlation of muscle mechanography with traditional muscle function tests suggests that it could. Jumping mechanography has already been integrated into prospective studies and outcome results should be available in the next few years.

CONCLUSION

Muscle mechanography is an innovative and safe research tool for measuring muscle function in older adults that offers several advantages to currently used methods. Muscle mechanography is consistent with the movement toward an increased use of highly innovative technology to quantitatively measure health status and outcomes. More research is needed to examine whether muscle mechanography can predict health outcomes such as falls, fractures, loss of independence, hospitalizations, and mortality.

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