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Review Article

Determinants of musculoskeletal frailty and the risk of falls in old age

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Abstract

Neuromuscular parameters that describe locomotion are indispensable variables for the diagnosis and treatment of frailty, fall risk and osteoporosis. A scientifically-based standardized locomotor assessment should be an essential part of medical examinations in research and clinical practice. There has been no previous consensus regarding which test procedures should be included in a locomotor assessment. The goal of this article is to provide a rationale for the selection of appropriate locomotor tests in a comprehensive locomotor assessment for elderly patients. We propose that a locomotor assessment should comprise the parameters that have been proven predictive for both falls and impending disability. The parameters should be measured in the standard units of physics. Therefore, we propose the following tests for a standardized locomotor assessment: (1) Self-selected gait velocity as the single best measure of general locomotor status and a good predictor of age-related adverse events; (2) Chair rise test (timed 5 chair rises) which measures power on vertical movement and the hip surrounding muscles as the most important neuromuscular risk factor for falls and fall-related fractures; (3) Tandem standing and tandem walking to measure postural capacity (balance) to the side; (4) Timed up and go test as a global screening procedure; (5) Clinical gait analysis with special focus on regularity; and (6) At least on a research level, movement must be measured referring to the terms of physics by mechanography. Mechanography (Leonardo force plate system, Novotec Pforzheim, Germany) records the time course of ground reaction forces, velocity of the vertical movements of the center of mass and power during unrestricted physiological movements. In the mechanogram the eccentric and concentric phases of movements can be differentiated and the storage of energy in the elastic elements of the body can be examined. The kinetics of human movement is explained by mechanograms of a two-legged jump. The ground reaction forces resulting from a jump down from a height of 0,46 m are demonstrated as a performance that is representative for human coordination. One goal of this text is to underline the insights that arise if the rules of physics are applied to human movement. A deeper understanding enables us to create more effective treatments for disorders of the muscle-bone unit. Bringing physics and cybernetics into the field of osteoporosis is a great heritage of Harold Frost.

Keywords: Mechanography, Age-related Falls, Locomotor Assessment, Muscle Power, Frailty

Locomotion plays a major role in prediction and prevention of age-related functional decline. Locomotor limitations are consistently and strongly correlated with falls, hip fractures, frailty, immobility and disability, which are all intertwined in a common pathogenetic pathway. Non-syncopal locomotor falls indicate the crossing of a critical threshold of locomotor competence, and can be seen as a manifestation of frailty, the precursor of disability. They are simultaneously the cause, consequence and an early indicator of the disabling process.

Locomotion and neuromuscular functions are also essential to the understanding and management of osteoporosis. Harold Frost has taught us that bone strength is determined by the habitual muscle forces which act upon the bones[1,2]. The steep age-associated increase in the incidence of non-vertebral osteoporotic fractures results from a combination of increased fall risk and reduced bone strength[3]. Whereas limitations of muscle power generate falls, decreased loading of bones, i.e., decreased muscle force, determines reduction of bone strength. Based on Wolff's Law, Harold Frost introduced the mechanostat, the concept of the mechanical con-

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• Manual muscle testing (MRC 1/5 to 5/5)
• Isokinetic measurements
• Isometric measurements
• One-repetition maximum
• EMG as surrogate for "muscle activity"
• Timed up and go test
• Tinetti Gait and Balance Scale
• Berg Balance Scale
• Short Physical Performance Battery (EPESE Score) of Guralnik, Ferrucci and co-workers with chair rise, tandem standing and gait velocity
• Maximal gait velocity
• Obstacle course
• Different concepts of clinical gait analysis
• Mechanography (Leonardo force plate)

Table 1. Examples of different methods used to measure neuromuscular functions.

force [Newton]	mass [kg] x acceleration [m/s]
work [Joule]	force [N] x distance [m]=force x velocity x time
power [Watt]	work [J] / time [s] =force x distance/ time =force [N] x velocity [m/s]
Example of a clinically relevant calculation with these parameters: A man of 70 kg body weight (~ about 700 Newton) climbs stairs of 3 m height within 10 or 3 s: 700 N x 3 m=2100 Joule 1) 2100 J/ 10 s=210 W 2) 2100 J / 3 s=700 W	

Table 2. Some basic definitions of physics, which are important for understanding movement.

trol loop of the muscle-bone-unit, in the field of osteoporosis. A growing number of studies give strong evidence for this concept ("Utah Paradigm"). Muscle function and locomotion are therefore issues of high priority in osteology and age-related medicine in general.

Neuromuscular parameters are, furthermore, indicators of frailty. Frailty is a new concept of increasing importance in geriatric medicine[4-20]. It is commonly seen as an age-related state of reduced physiological reserve, a distinct clinical syndrome strongly correlated with a high risk of common age-associated negative health outcomes such as death, disability, hip fractures, a need for long-term care and hospitalization. The clinical significance of frailty is apparent in the time course of the disablement process. Frailty is a transient period before the onset of disability and perhaps the most appropriate life period for prevention of disability. Frailty encompasses a variety of important health determinants that are not conceptualized by disease or disability. Therefore, locomotion and the parameters describing the underlying neuromuscular functions are indispensable variables for the diagnosis and treatment of elderly patients. A scientifically-based standardized locomotor assessment should be an essential part of a medical examination in research and clinical practice.

Unfortunately there is a great diversity in the methods that are used to quantify locomotion and neuromuscular functions (Table 1). Furthermore some concepts of neuromuscular diagnostics are not consistent with the rules and definitions of physics. One of the most common pitfalls in medical articles is to mix up the terms "strength" and "power". Table 2 lists the essential definitions of physics referring to movement. For understanding bone strength and fall-related fractures, the differentiation between force and power is crucial. Whereas bone strength is determined by the maximal *muscle forces*, which the bones are habitually loaded with, preventing falls is determined by *muscle power*, the product of force and velocity. The differentiation between force and power is therefore essential for the development of appropriate treatment regimens.

There has been no previous consensus regarding which test procedures should be included in a locomotor assessment. The goal of this article is to provide a rationale for the selection of appropriate locomotor tests in a comprehensive locomotor assessment for elderly patients. We propose that a comprehensive locomotor assessment should comprise the parameters that have been proven predictive for both falls and impending disability. The parameters should be measurable in the standard units of physics.

Guralnik, Ferrucci and co-workers[21,22] can have found that the combined result of three tests of lower extremity function is an independent, strong predictor of morbidity, hospital admission, incident disability, mortality and admission to a nursing home. Their short physical performance battery consists of 1) self-selected gait velocity, 2) timed 5 chair rises, and 3) the combination of Romberg, semi-tandem and tandem standing[21]. Later research has confirmed their findings. Gait velocity has repeatedly been proven to be an indicator of future functional decline and adverse events[22], and chair rise tests and tandem manoeuvres, have been proven to be independent fall risk factors.

Therefore we propose the following tests for a standardized locomotor assessment: (1) Self-selected gait velocity as the single best measure of general locomotor status and a good predictor of age-related adverse events; (2) Chair rise test (timed 5 chair rises) to measure power on vertical movement and the hip surrounding muscle function as the most important neuromuscular risk factor for falls and fall-related fractures; (3) Tandem standing and tandem walking to measure postural capacity (balance) to the side; (4) Timed up and go test as a global screening procedure; (5) Clinical gait analysis with special focus on regularity of steps; and (6) At least on a research level, movement must be measured referring to the terms of physics by mechanography.

Of course, an appropriate locomotor assessment is embedded in a physical examination with emphasis on fall history and history of development of locomotor activity dur-

1. Muscle power of lower extremities on arising from sitting
2. Postural competence, i.e., lateral balance
3. Impairment of vision
4. Taking multiple medications (>4) or
5. Taking certain groups of fall-related drugs: antidepressants, neuroleptics, benzodiazepines, anticonvulsivants
6. Cognitive impairment

Table 3. Independent fall risk factors[23-35].

Manual muscle testing	poor interrater reliability
Isometric testing	movement by definition excluded
Isokinetic testing	slow velocity in comparison to fall-evasion movements, artificial positioning of the body
1RM (1 repetition maximum)	differs depending on machine properties with different friction, slow velocity compared to fall-evasion movements
Performance-oriented tests	high diversity of different test procedures, difficult to refer the results to physics of movement

Table 4. Limitations of different methods used to measure neuromuscular functions.

ing the last years. The proposed assessment includes the factors, which have been found most consistently and strongly correlated with falls (Table 3).

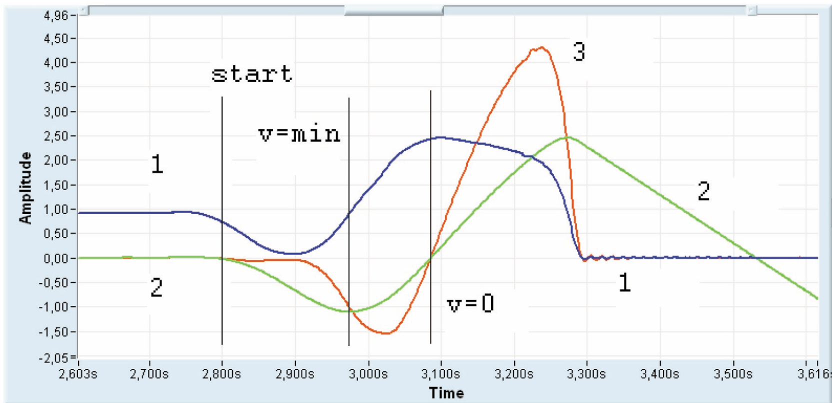
The assessment is suited to identify the determinants of falls and functional decline and also to evaluate interventions. The deterioration of locomotor and balance functions associated with advancing age can be counteracted by gait and balance training. Corresponding to the multifactorial pathogenesis of falling, frailty and disability, multifaceted interventions have been proven effective in preventing falls and other adverse events and improving functional status. The exercise programs have included Tai Chi, balance training, strength resistance training and revision of medication[36-40].

Measuring locomotion with everyday manoeuvres is feasible and clinically meaningful, but this methodology has certain limitations. Different investigators have used different arrangements and environments for testing locomotion, and the results of timed performance-oriented tests are difficult or impossible to equate to force and power. Results are therefore not directly comparable, and the reference to animal models is difficult or excluded. If movements are described referring to physics, these limitations can be overcome. Table 2 denotes the formulae and definitions that are necessary for a correct measurement of movement. Force is defined as that which causes deformation or acceleration. Movement is, however, the action of force along a distance in a certain time, and must therefore be measured as power. Power is a necessary parameter to measure movement. Measuring force as a single parameter by isometric manoeuvers, means exclusion of movement. The calculation in Table 2 demonstrates a description of stair climbing as a clinically meaningful example of measurement of movement: how can the performance of stair climbing be measured? Stair climbing at a usual pace is done with an average power of 3 watt per kg body weight, and a fit person generates 10 watt per kg body weight during a stair climbing of 3 m at maximal pace. The maximal power, which is generated by a locomotor task, and not the force, corresponds to the cardiovascular effect, the subjective perception of exertion and the locomotor level of a person.

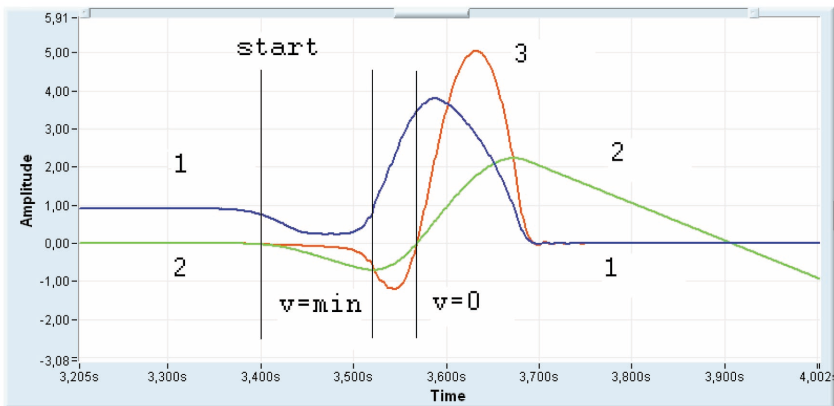
The Leonardo force plate system, invented and constructed by Hans Schiessl (Novotec Pforzheim, Germany) measures force and calculates by integration of acceleration the vertical velocity of the Center of Gravity ($F/m = a$; $a \times t = v$), and the power of vertical movements. The term "mechanography" has been coined for this method, which records the time course of ground reaction forces, velocity of the vertical movements of the COG and power during unrestricted physiological movements. The authors are not aware of any other commercially available force plate that is able to perform these calculations. The Leonardo system has been used in published studies[41,42] and is used in clinical practice. In the mechanogram, the eccentric and concentric phases of movements can be differentiated and the storage of energy in the elastic elements of the body can be examined (Figure 1). Why is the assessment of the eccentric motor action essential? Without the release of previously stored energy, the motor system cannot quickly enough produce the energy necessary to jump. The force we need for a movement against gravity is the summation of quickly released energy which has been previously stored in elastic elements during eccentric countermovements, and muscle force currently being generated by the actin-myosin system. During the eccentric phases the elastic elements are stretched by which energy is stored. The Leonardo system enables us to analyze these eccentric phases, which have been proven to be most sensitive to motor disorders and which provide early and pathognomonic signs of motor disorder. In contrast to this kind of measurement, the commonly used muscle testing methods have certain shortcomings. Isometric motor tests are by definition without movement and therefore cannot reveal the above-mentioned aspects. Isokinetic testing does not represent important characteristics of physiological movements, being restricted to slow velocities and an artificial time course (Table 4).

One standard procedure of mechanography is the recording of a vertical two-legged jump of maximal exertion (Figure 1). Jumping represents the opposite to falling. The first phase of jumping is squatting. On relaxing the muscles gravity accelerates the body weight downwards. Before reaching the deepest point of squatting, the muscles decelerate the downward movement by an eccentric muscle action, which

1a



1b



1a: Jumping as high as possible=jumping with highest final velocity (get the banana)
1b: Jumping with high stiffness=high force, i.e., moving as quickly as possible from the spot=jumping with maximal force (get away from the snake)

Kinetic parameters of the 2 jumps

parameter	1a "as high as possible" get the banana	1b "as quick and hard as possible" get away from the snake
height [m]	0.40	0.34
maximal force [N]	2450	3800
maximal velocity [m/s]	2.45	2.23
maximal Watt/ kg BW	46.07	54.01

Line 1 represents the force, line 2 the vertical velocity of the center of mass, line 3 the power.
x-axis=amplitude of the parameters, y-axis = time course (ms).
The time between the first and third vertical marker (start to v=0) is the countermovement, i.e., going down to a squatting position. Deceleration and energy storing begins at the second vertical marker (v=min). Decisive for the final height and velocity is the amount of energy which is generated during the movement. Energy during jumping can be calculated as the product of force x velocity x time. Please pay attention to the duration of the countermovement (different scale!).

Figures 1a,b. Figures a,b represent two different kinds of 2-legged jump. Male subject M.R., 93.4 kg, age 56.

stretches the muscle-tendon-unit.

The velocity curve (Figure 1) shows that during the first half of the squatting an acceleration downward, i.e., a growing negative velocity. The nadir of the velocity curve denotes the beginning of the deceleration, the downward movement slows down. The mechanism of this phase is a stretching of elastic elements, which means that kinetic energy is now being stored in the muscle-tendon-unit. When the squatting movement reaches its deepest point, the velocity curve crosses the zero line. At this point in time, kinetic energy has been transformed to potential energy, stored in the elastic elements (spring-like). At this phase the ground reaction force is approaching its highest value. The situation of the body is comparable to an arrow in a stretched bow. Now the stored energy can be released very fast, and contributes significantly to the whole amount of energy that is necessary for jumping. Jumping without previous elastic storage of energy is effectively not possible, because the rate of energy pro-

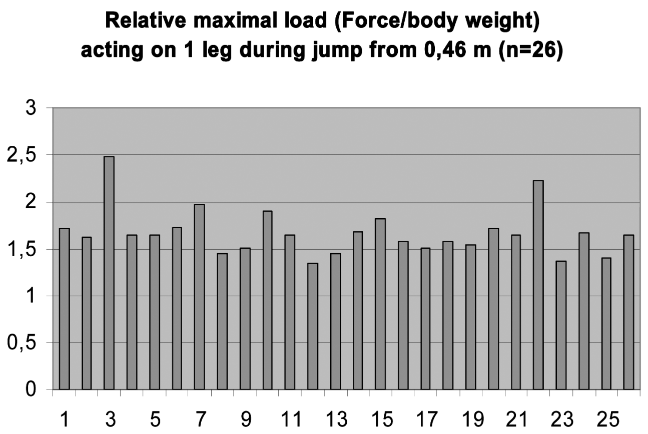


Figure 2. Relative maximal loads (force/body weight) acting on 1 leg during jump from a height of 0,46 cm. n=26, convenience sample of fit adult persons. Absorbing kinetic energy within milliseconds represents a high coordinative performance which protects the body structures against overloading.

duction by the actin-myosin cross-links is not sufficient for fast movements against gravity. With increasing velocity the force curve decreases, representing the inverse relationship between force and velocity that has first been described by Hill (Hill‘s equation). The mechanogram enables the real-time recording of force, velocity and power during those everyday movements, which have been proven meaningful for falls and frailty. Comparison of mechanography with usual locomotor tests has demonstrated its high reproducibility[41]. The muscle power on jumping, measured by mechanography, shows a strong correlation to the aging process[42], proving its high clinical significance.

Mechanography gives a number of other insights into human movement, the details of which are beyond the scope of these introductory remarks. An important issue for further research is measuring the ground reaction forces, which are generated during different exercises. For planning appropriate osteoanabolic exercises we need knowledge about forces acting on bone. Is a certain exercise able to generate sufficient strain? In an ongoing study we are investigating the ground reaction forces of different exercises for an osteoporosis-specific program. Figure 2 depicts the maximal ground reaction forces which act on one leg during jumping from a height of 0.46 m, trying to land on the ground as softly as possible. The data are recorded from a convenience sample of completely fit volunteers (age below 60 years). The test represents the ability of the motor system to adapt within ms its stiffness to the exact amount, which is necessary to damp the kinetic energy of the downward movement. Beside generating energy (act as a motor) and storing energy (act as a spring) this is the third function of a muscle: to absorb kinetic energy (act as a damper) in order to come to a standstill. The shock absorbing ability of the motor system is not only decisive for controlling movement, but also to minimize the peak forces that act habitually on the body. Given a certain kinetic energy of the moving body the motor system has to create a "crumple zone" to minimize the forces loaded on body structures, for deformation and damage of bone, tendons and cartilage depend on the number and amount of loaded forces. Referring to physics co-ordination can be defined as the ability to adapt the stiffness of various body parts to the demands of a given locomotor task. The "jump down test" gives insight into the damping and co-ordinative capacity of a person.

One goal of this text is to underline the insights that arise if the rules of physics are applied to human movement. A deeper understanding enables us to create more effective treatments for disorders of the muscle-bone unit. Bringing physics and cybernetics into the field of osteoporosis is a great heritage of Harold Frost.

With gratitude dedicated to the memory of Harold Frost.

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