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Original Article

Reproducibility of jumping mechanography in healthy children and adults

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Abstract

Objectives: To describe mechanographic tests that can be performed by patients with a range of functional abilities and to assess the reproducibility of test results in healthy adults and children. **Methods:** Fifteen adults and 13 children underwent two separate sessions, one week apart. Participants performed five different tests in both sessions: Multiple one-legged hopping, multiple two-legged hopping, single two-legged jump, heel-rise test, chair-rise test. All measurements were recorded with a portable force platform. **Results:** The main outcome measures of each test (peak force relative to body weight or peak power relative to body weight, depending on the test) showed no systematic differences between Session 1 and 2 for any of the test results. Coefficients of variation for the suggested main outcome parameters ranged between 3.4% and 7.5% for multiple one-legged hopping, multiple two-legged hopping, single two-legged jump and the heel-rise test, but were higher for the chair-rise test (8.0% in adults, 15.6% in children). **Conclusions:** The five mechanographic tests assessed in the present study yield reproducible outcome measures in healthy subjects. It is justified to evaluate the usefulness of these tests in different patient populations.

Keywords: Ground Reaction Force, Jump, Muscle Function, Power, Velocity

Introduction

Many chronic disorders affect muscle function in children and adolescents. This is not only true for 'classical' muscular or neuromuscular diseases, such as Duchenne muscular dystrophy or cerebral palsy, but also for many other chronic disorders. Indeed, conditions as diverse as chronic renal failure, Crohn's disease, osteogenesis imperfecta and congenital heart disorders all lead to deficits in muscle function[1-4]. Nevertheless, the diagnostic armamentarium for evaluating muscle function in the clinical context is rather limited. Apart from rating a patient's 'muscle strength' subjectively on a scale from 0 to 5 during physical examination, measurement of grip force by dynamometry is probably the most widely available test. However, the grip force test only assesses isometric force at the upper extremity. Kinematic and kinetic analyses in human movement laboratories yield far more detailed information but are not widely available and are very time consuming.

Portable ground reaction force plates could be useful for assessing some aspects of dynamic muscle function in clinical settings and have been used in a number of clinical studies[4-9]. This approach is commonly called 'jumping mechanography'[4-6,8,9]. Most of the published mechanographic studies assessed muscle function during a vertical countermovement jump test for maximal height. Although this test is easy to perform in healthy subjects and in patients with mild muscle weakness, many patients with more severe motor deficits or lower limb deformities are unable to jump. In order to make use of mechanography in the clinical setting, a larger variety of mechanographic tests is needed that covers a spectrum of functional abilities.

When a test is to be established for clinical use, it is important to describe the test procedures with sufficient detail so that others can reproduce it. It is also important to assess basic test characteristics, such as the test-retest variability of results. The aims of the present study therefore were to describe mechanographic tests that can be performed by patients with a range of functional abilities and to assess the reproducibility of outcome measures in healthy children and healthy young adults.

The authors have no conflict of interest.

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Parameter[a]	Definition	Unit	Determined in
F_{max}	Maximum force; both sides combined	kN	All tests
F_{max} left	Maximum force for the left leg	kN	M1LH, S2LJ
F_{max} right	Maximum force for the right leg	kN	M1LH, S2LJ
F_{max}/BW	Maximum force per body weight	No Unit	All tests
Height	Maximum jumping height (maximal upward displacement of the body's center of gravity)	m	S2LJ
P_{max}	Maximum (peak) power during upward movement	W	S2LJ, HRT, CRT
P_{max}/mass	Maximum power per body mass during upward movement	W/kg	S2LJ, HRT, CRT
P_{max} left	Maximum (peak) power for the left leg during upward movement	W	S2LJ
P_{max} right	Maximum (peak) power for the right leg during upward movement	W	S2LJ
pP_{max}/mass	P_{max}/mass expressed as a percentage of the mean of age- and gender-specific reference range	%	S2LJ
V_{max}	Maximum (peak) velocity during upward movement	m/s	S2LJ, HRT, CRT

[a]*All force-based measurements take only into account the vertical component of force.*

Table 1. Definition of the jump parameters used in the present study.

Subjects and Methods

Study Population

Fifteen healthy adults (8 females, 7 males; age range: 24 to 44 years; mean weight [SD] 67.3 [15.3] kg; mean height 167 [12] cm) and 13 children (5 females and 8 males; age range 7.1 to 11.1 years; weight 33.2 [8.6] kg; height 134 [10] cm), took part in this study. Adult participants were employees of the Shriners Hospital for Children in Montreal, Canada. The pediatric group was comprised of children of hospital employees and their friends. Participants were excluded if they reported any disorder that might interfere with their ability to perform the tests. Participants or their parents provided informed consent. This study was approved by the Ethic Research Office of the Faculty of Medicine of McGill University.

Measurement Equipment

The Leonardo Mechanograph® Ground Reaction Force Plate (Novotec Medical GmbH, Pforzheim, Germany) is a force platform with a length of 66 cm, a width of 66 cm and a height of 7 cm. The platform is composed of two symmetrical force plates that separate the platform into a left and a right half. The resonance frequency of each plate is at 150 Hz. Each plate contains four strain gauge force sensors (the whole platform thus has eight force sensors). The force sensors measure the vertical ground reaction force exerted on the platform. The sensors are connected to a laptop computer via a USB 2.0 connection. The signal from the force sensors is sampled at a frequency of 800 Hz and is analyzed using the Leonardo Mechanography GRFP Research Edition® software (in this study version 4.2-b05.53-RES was used).

Accuracy and Precision of Static Force Measurements

Static properties of the force plate were assessed by applying combinations of one 10 kg and three 20 kg cast iron grip handle weights (ISO 9001, Troemner, NJ, USA) to the force plate. The weights were certified to deviate from the indicated nominal value by less than 0.01% (Reference Standards Traceable of the United States National Institute of Standards and Technology). The weights were in turn applied on one of four locations (1. the front half of the right force plate; 2. the back half of the right force plate; 3. the back half of the left force plate; 4. the front half of the left force plate). This procedure was performed three times, thus providing 12 measurements at each weight. From these 12 measurements, accuracy (mean difference of the measurements from the reference weight) and precision (coefficient of variation, CV, of repeated measures at the same weight, corresponding to the ratio of the standard deviation and the mean result of the 12 measurements, expressed as a percentage) were computed at each weight. In addition, the maximal deviation from the reference weight was recorded at each weight.

The combined weight of the calibrated weights was 686.5 N, which is far below the highest forces measured during the testing of study participants (close to 5000 N). In order to assess precision of static force measurements at forces above 686.5 N, 12 weight measurements were performed with four adult subjects standing on the force plate simultaneously.

Outcome Parameters (Table 1)

A subject's body mass is assessed during quiet stance immediately before each trial. The software calculates instantaneous vertical velocity (v) of the subject's center of gravity by time integration of the instantaneous vertical acceleration (a), as described in principle by Cavagna[10]:

$$(1)\ v = \int_0^t a\ dt = \frac{1}{m}\int_0^t (F-BW)\ dt$$

where F is the instantaneous vertical force applied to the platform, BW is the subject's body weight, and m is the subject's body mass.

Instantaneous power (P) is calculated as the product of F and v. Peak power (P_{max}) is defined as the maximal power output measured during the initial acceleration phase of a test. The ratio

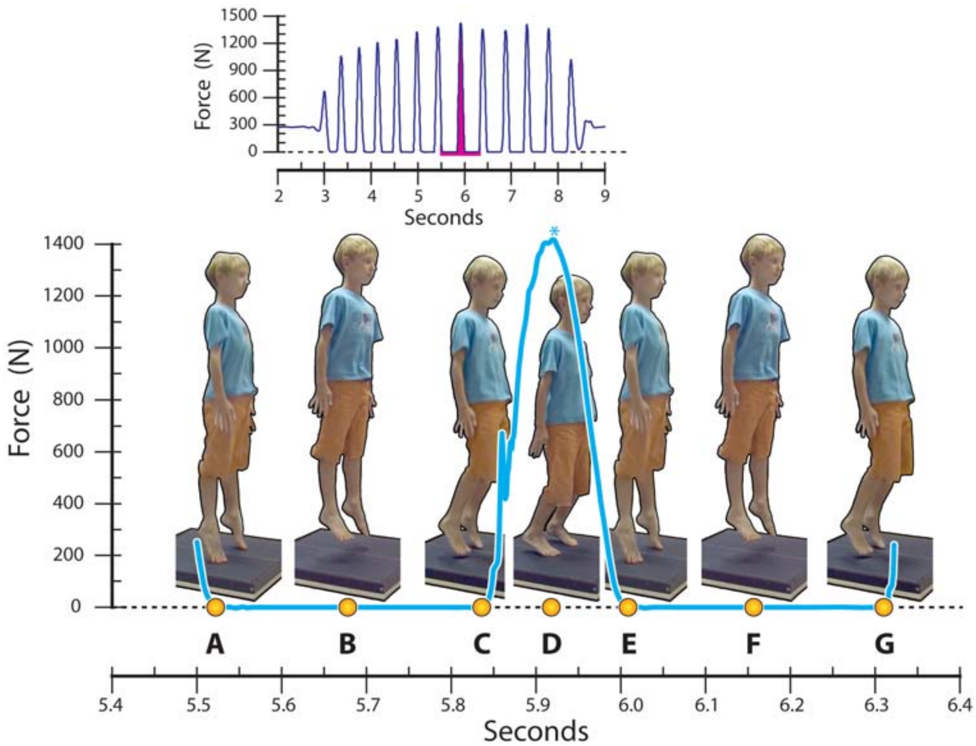

Figure 1. Multiple two-legged hopping. About 10 hops on both forefeet and with stiff knees are recorded. The small upper graph shows the recording of the entire test. The highest peak of the series is highlighted. The larger graph shows a magnification of the highest peak and the phases of the movement corresponding to the indicated points on the Force-Time curve. **A.** Take-off. **B.** Highest point of the hop. **C.** Landing. **D.** Lowest point after landing. Note that the heels do not touch the ground. **E.** Take-off. F. Highest point of the hop. **G.** Landing. The asterisk on the Force-Time curve indicates F_{max} for this test.

between P_{max} and the subject's body mass is a potentially useful outcome parameter for tests where the aim is to achieve maximal speed. For example, the software includes reference ranges for the P_{max}/mass ratio during the vertical countermovement jump. These reference ranges are based on studies that were performed on healthy German subjects from 6 to 88 years of age[5,11]. P_{max}/mass expressed as a percentage of the mean value of the age- and sex-specific reference range is called 'Esslinger Fitness Index (EFI)' in this software. However, this generic term does not make clear what type of measurement it refers to. In this report we therefore use the abbreviation pP_{max}/mass to denote 'P_{max}/mass expressed as a percentage of the mean value of the age- and sex-specific reference range' in the vertical countermovement jump, corresponding to the 'Esslinger Fitness Index'.

The time integration of P yields instantaneous kinetic energy (E_{kin}). In the single two-legged jump (described below) the body's maximal kinetic energy is converted into potential energy (E_{pot}) until the body's center of gravity reaches the maximum height above the force plate (energy loss through air friction being neglected). Maximum jump height (h) can thus be derived from the maximal E_{kin} and the subject's body mass (mass) as follows:

(2) (Maximal E_{kin}) = (Maximal E_{pot}) = h x mass

(3) h = (maximal E_{kin})/mass

Test Procedures

Prior to each test in each participant, the experimenter provided a description of the procedure and a physical demonstration of the task. The force platform was adjusted to indicate a mass of zero kg before a subject stepped onto it. The participant stood on the device in an upright position, with one foot on each side of the platform. Body mass was recorded once the participant stood still for at least 2 seconds. Following a single-tone pitch, the participant performed one of the test maneuvers described below. After each trial, the participant remained still for at least 2 seconds. The termination of the test was indicated by a double-tone pitch. In the following description of the various tests we employ the same terminology as the software that was used to evaluate the results.

Multiple Two-Legged Hopping (M2LH, Figure 1): This represents two-legged hopping on the forefoot with the aim to achieve a maximal ground reaction force. In previous versions of the software, this test was called multiple two-legged jump. One possible application of this test is to evaluate the maximal force to which the tibia is exposed, and thus might serve to evaluate the muscle-bone unit[12]. The instructions were as follows: "Hop on both forefeet with stiff knees and without touching the ground with your heels. Hop as high as possible

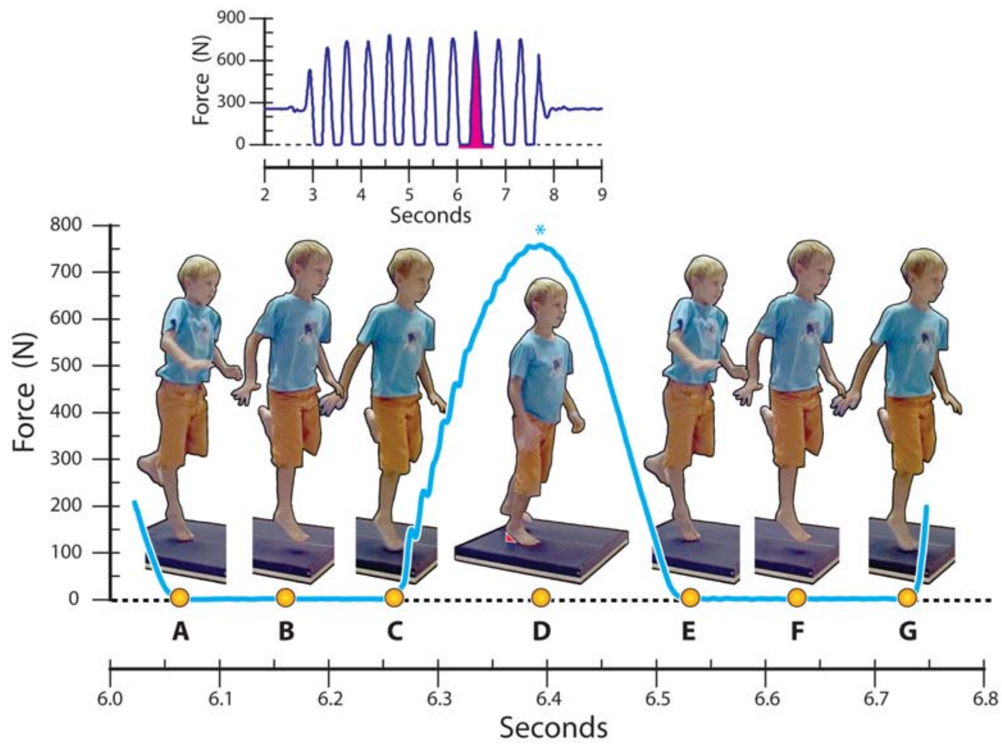

Figure 2. Multiple one-legged hopping. About 10 hops on one forefoot and with stiff knees are recorded. The small upper graph shows the recording of the entire test. The highest peak of the series is highlighted. The larger graph shows a magnification of the highest peak and the phases of the movement corresponding to the indicated points on the Force-Time curve. **A.** Take-off. **B.** Highest point of the hop. **C.** Landing. **D.** Lowest point after landing. Note that the heels does not touch the ground (as highlighted by the red wedge between the heel and the plate). **E.** Take-off. **F.** Highest point of the hop. **G.** Landing. The asterisk on the Force-Time curve indicates F_{max} for this test.

in that way for about 10 times". The software automatically detected and eliminated from the analysis those hops in which a heel hit the ground. The 'best' trial was the one with the highest maximum force (F_{max}) during a hop. F_{max} and F_{max}/BW were analysed for this hop. F_{max}/BW was considered the main outcome parameter.

Multiple One-Legged Hopping (M1LH, Figure 2): This is a one-legged hopping test with the aim to achieve a maximal ground reaction force. In previous versions of the software, this test was called multiple one-legged jump[8]. Similar to the M2LH, a possible application of this test is to evaluate the maximal force to which the tibia is exposed. The instructions were as follows: "Hop on one forefoot with stiff knees and without touching the ground with your heel. Hop as high as possible in that way for about 10 times." The software automatically detected and eliminated from the analysis those hops in which the heel hits the ground. The 'best' trial was the one with the highest Fmax during a hop. F_{max} and F_{max}/BW of the left and the right legs were analysed for this hop. F_{max}/BW was considered the main outcome parameter for the multiple one-legged hopping.

Single Two-legged Jump (S2LJ, Figure 3): This is a vertical countermovement jump to achieve maximum jump height. Test results are influenced by a variety of factors, such as muscle power, coordination, balance, and jumping technique. It might therefore be regarded as a 'screening test' for anaerobic fitness[13]. The instructions were as follows: "Jump once with both legs, as high as possible. You can swing your arms to help with the jump. Stand upright before and after the jump." The participant performed one jump per trial. The 'best' trial was the one with the highest jump height. This trial was used for further analysis. Parameters used for analysis were: F_{max} (both legs combined, as well as left and right leg analyzed separately), F_{max}/BW, height, P_{max} (both legs together and left and right leg independently), P_{max}/mass, pP_{max}/mass and vmax. P_{max}/mass was considered the main outcome parameter for the single two-legged jump.

Heel-Rise Test (HRT, Figure 4): In the literature, the HRT is often described as an endurance test which measures how many unilateral heel rises can be performed when standing on a single foot[14]. In the present study, a different type of HRT was performed. It consisted of five bilateral heel rises with the aim to achieve maximal speed of the upward movement in the first heel-rise of each trial. This test was introduced with the idea that it could be performed also by patients who are unable to jump or who are unable to perform a sit-to-stand movement (see below). The instructions were as follows: "Rise to the tip of your toes 5 times in a row as fast as possible. It is important

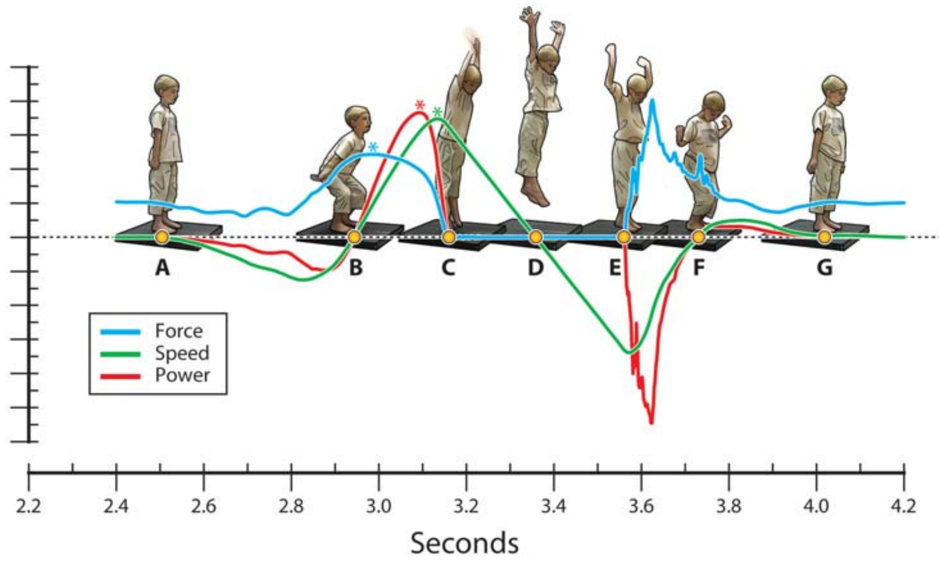

Figure 3. Single two-legged jump. One countermovement jump to maximal height with swinging arms is recorded. The Force-Time, Speed-Time and Power-Time curves are shown as well as the phases of the movement corresponding to the indicated points on the Speed-Time curve. **A.** At rest. **B.** Lowest point of the countermovement. **C.** Take-off. **D.** Highest point of the jump. **E.** First impact of landing phase. **F.** Lowest point after landing. **G.** At rest. The blue, green and red asterisks indicate F_{max}, V_{max} and P_{max} for this test, respectively.

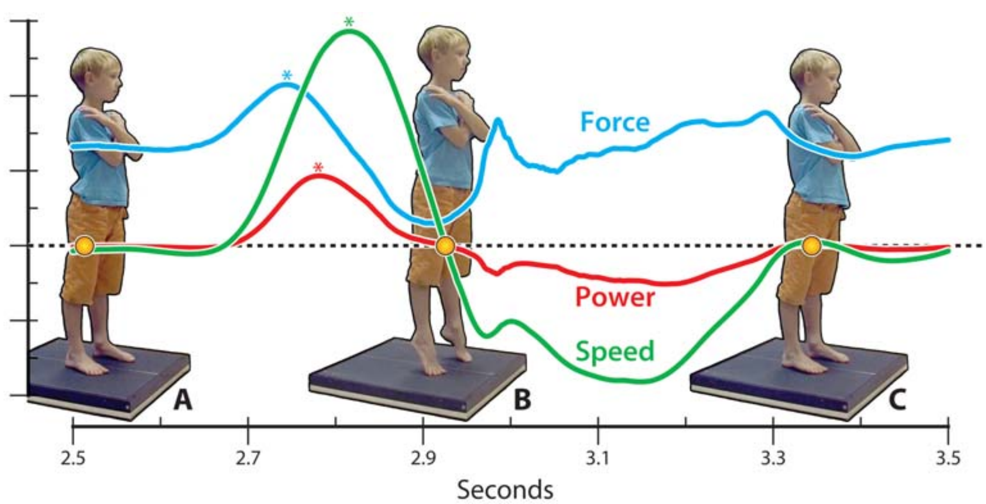

Figure 4. Heel-rise test. The first movement to a position on tiptoes is recorded. The Force-Time, Speed-Time and Power-Time curves are shown as well as the phases of the movement corresponding to the indicated points on the Speed-Time curve. **A.** At rest. **B.** Highest point of the movement. **C.** At rest. The blue, green and red asterisks indicate F_{max}, V_{max} and P_{max} for this test, respectively.

that you keep your knees straight. Cross your arms on your chest and grab your shoulders with your hands. Move to your tiptoes as fast as possible in this way."

Only the first upward movement was evaluated by the software. The idea of nevertheless performing five heel rises was that the repetitive movement would result in a more 'natural' movement pattern also during the first heel rise. An HRT trial was only considered valid if the first upward movement occurred without countermovement. A countermovement was said to have occurred if the velocity curve of the test showed a negative speed (indicating a downward movement of the body's center of gravity) of more than -0.03 m/s before the upward movement. The 'best' trial was the one with the highest maximum force (F_{max}) during the first upward movement. F_{max} and F_{max}/BW, P_{max}, P_{max}/mass and Vmax were analysed for this trial. F_{max}/mass was considered the main outcome parameter for the HRT.

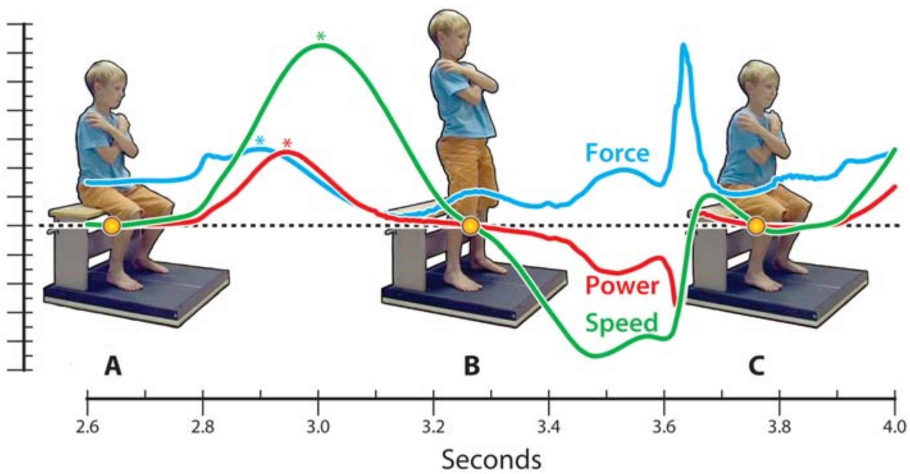

Figure 5. Chair-rise test. The second of five sit-to-stand repetitions is recorded. The Force-Time, Speed-Time and Power-Time curves are shown as well as the phases of the movement corresponding to the indicated points on the Speed-Time curve. A. At rest. B. Highest point of the movement. C. At rest. The blue, green and red asterisks indicate Fmax, Vmax and Pmax for this test, respectively.

Chair-Rise Test (CRT, Figure 5): This is a sit-to-stand test with five repetitions. The test made use of a bench that was anchored to the force plate for the purpose of this test. The rationale for using this test is that it should allow measuring muscle power in patients who are not able to jump. In addition, this test evaluates a movement that is highly relevant in everyday life. The forces that arise during the sit-to-stand test depend on bench height[15]. In this study, a bench with a height of 46 cm was used for subjects with a body height of 145 cm or more. For participants with a height below 145 cm, a bench with a height of 34 cm was used. The instructions were as follows: "You start by sitting on the bench with the feet on the ground. Cross your arms on your chest and grab your shoulders with your hands. Stand up until you are standing completely straight and instantly sit down again as fast as you can. Repeat this five times".

The mechanographic data of the second rise were used for analysis as this was the rise with the best automatic peak detection (data not shown). Even though only the second rise was assessed, participants nevertheless were asked to perform five up-and-down movements, in analogy to the CRT that is commonly performed for the assessment of geriatric patients[16]. In geriatric use, the main outcome parameter is the time that is required to perform the five repeat movements. This might also be a useful test for young patients with motor impairment. In healthy young subjects, however, there is a clear ceiling effect and therefore the time to perform 5 repeat chair rises was not evaluated here. The 'best' trial was the one with the highest maximum power (P_{max}). F_{max}, P_{max}, P_{max}/BW and Vmax were analysed. P_{max}/mass was considered the main outcome parameter for the CRT.

Testing Strategy

Inter-day test-retest reliability was evaluated by the same observer in two sessions separated by one week. In each session, the tests were performed in the following order: M2LH, M1LH, S2LJ, HRT, CRT. Three valid trials were performed for each test. Depending on the test, a trial was defined as a single jump (for the S2LJ) or as a series of 5 (HRT and CRT) or about 10 consecutive vertical up-and-down movements (M1LH and M2LH). Results of the 'best' trial were recorded as the final result of the test in each of the two test sessions.

Weight (N)	Deviation (%)	Max Deviation (%)	CV (%)
98.1	0.66 (0.05)	1.3	0.46
196.1	0.69 (0.05)	1.2	0.27
294.2	0.78 (0.05)	1.1	0.17
392.3	0.75 (0.09)	1.0	0.22
490.4	0.67 (0.10)	1.1	0.20
588.4	0.78 (0.13)	1.2	0.21
686.5	0.71 (0.17)	1.2	0.24

Weight: calculated as (mass multiplied by 9.807 N/kg). Deviation: (measurement result – nominal weight) / (nominal weight), expressed as percentage, mean (SD). Max deviation: Largest deviation of a single force measurement from the nominal weight. CV: Coefficient of variation of 12 force measurements at each weight.

$CV = \frac{SD}{\overline{X}} \times 100$, *where SD is the standard deviation and* $\overline{X}$ *the mean of the 12 measurements.*

Table 2. Results of static force measurements using calibrated weights.

Statistical Analysis

All calculations were performed using PASW 18® (SPSS Inc., Chicago, IL, USA). Systematic bias was assessed by calculating the change in the mean between the two testing sessions using paired t-tests.

	Adults (N = 15)			Children (N = 13)		
	Session 1	Session 2	P	Session 1	Session 2	P
Multiple Two-Legged Hopping						
F_{max} (kN)	3.41 (0.69)	3.34 (0.71)	0.55	1.66 (0.42)	1.72 (0.38)	0.14
F_{max}/BW	5.21 (0.62)	5.12 (0.86)	0.55	5.30 (0.49)	5.45 (0.59)	0.22
Multiple One-Legged Hopping Left Leg[a]						
F_{max} (kN)	2.00 (0.38)	1.97 (0.37)	0.10	0.99 (0.24)	0.97 (0.24)	0.26
F_{max}/BW	3.07 (0.35)	3.00 (0.27)	0.74	3.15 (0.38)	3.03 (0.25)	0.12
Multiple One-Legged Hopping Right Leg						
F_{max} (kN)	2.04 (0.40)	1.99 (0.38)	0.14	0.98 (0.22)	0.99 (0.23)	0.62
F_{max}/BW	3.12 (0.37)	3.04 (0.32)	0.08	3.14 (0.45)	3.12 (0.37)	0.71

[a]N= 14 in the adult group, as one participant had invalid results due to a technical problem. The P value indicates the significance of difference between the result of Session 1 and Session 2.

Table 3. Mean (SD) results of 'force tests' in two separate test sessions.

Two measures of reproducibility were calculated, CV and intraclass correlation coefficient (ICC). The CV is the usual measure of variability in most scientific fields, but the ICC is in addition widely reported in rehabilitative sciences. Therefore, the ICC is presented here to allow for comparisons with other studies.

For each parameter, the CV was calculated separately for the adult and the children group. The CV corresponds to the SD divided by the mean of all measurements, expressed as a percentage. SD was calculated as follows[17]:

$$SD = \sqrt{\sum_{J=1}^{n} \frac{d_J^2}{2n}}$$

where d_j is (Result in Session 1) – (Result in Session 2) of Subject j, and n is the number of subjects.

Regarding ICC, a two-way mixed effect model with a consistency definition was used following the algorithm proposed by McGraw and Wong[18]. In the mixed model the participant is treated as a random effect, whereas measurement error is considered as a fixed effect. Thus, ICC(C,1) and their 95% confidence intervals (95% CIs) were computed.

Results

To assess accuracy, static weight measurements were performed in the range from 98.1 N to 686.5 N. The device used in this study was found to systematically overestimate the reference weights by 0.66% to 0.78% (Table 2). The maximal deviation from the reference weight in any of the 84 static measurements performed in this study was 1.3%. As to precision, the CV for 12 repeated measurements was 0.46% for the smallest weight used in this study (98.1 N), and below 0.30% for the larger weights. Precision was also determined at higher force levels, by performing 12 separate weight measurements of four adult subjects who stood on the platform simultaneously. This yielded an average weight measurement of 2940.5 N, with an SD of 2.7 N, resulting in a CV of 0.09%.

In order to facilitate the presentation of results, the battery of tests performed in this study was separated into tests that aim at achieving maximum force (called 'force tests': M2LH, M1LH) and tests that are targeted to achieve maximum velocity (called 'speed tests': S2LJ, HRT, CRT; achieving maximum height in the S2LJ corresponds to achieving maximal take-off speed). No systematic differences were observed between results of Session 1 and 2 for any of the parameters (Tables 3 and 4).

The inter-day variability of weight measurements in study participants was 0.59% for adults and 0.99% for children. Reliability measures (CV, ICC) for 'force tests' are shown in Table 5. For both adults and children, CVs were lowest for the M1LH on the right leg. Children had slightly lower CVs than adults in the M2LH, but slightly higher CVs in the M1LH. In contrast ICCs were higher in children than in adults for all but one parameter (F_{max}/BW in the M2LH).

Reliability measures for 'speed tests' are shown in Table 6. In the S2LJ, power parameters and jump height had CVs between 3.4% and 5.8%, whereas CVs for force parameters were much higher. The lowest variability was found for V_{max}. In the HRT, variability was lowest for force parameters, with CVs between 3.3% and 5.7%, but much higher for velocity and power parameters. Among all tests, the CRT had the largest variability in its main outcome parameter (P_{max}/mass), with a CV of 8.0% in adults and 15.6% in children.

Discussion

In the present study we describe five mechanographic tests (M2LH, M1LH, S2LJ, HRT, CRT) that are proposed for assessing muscle function in patients with a variety of functional abilities. As a first assessment of their validity, we evaluated reproducibility in healthy children and in healthy young adults.

	Adults (N = 15)			Children (N = 13)		
	Session 1	**Session 2**	**P**	**Session 1**	**Session 2**	**P**
Single Two-Legged Jump						
F_{max} (kN)	1.54 (0.36)	1.54 (0.45)	0.88	0.78 (0.24)	0.76 (0.16)	0.56
F_{max}/BW	2.35 (0.37)	2.31 (0.34)	0.57	2.47 (0.61)	2.38 (0.27)	0.55
F_{max} left (kN)	0.76 (0.19)	0.78 (0.26)	0.38	0.42 (0.20)	0.37 (0.09)	0.29
F_{max} right (kN)	0.80 (0.17)	0.80 (0.22)	0.85	0.39 (0.12)	0.39 (0.08)	0.96
Jump Height (m)	0.42 (0.11)	0.42 (0.11)	1.00	0.37 (0.04)	0.37 (0.04)	1.00
P_{max} (W)	3.02 (1.15)	3.09 (1.28)	0.28	1.32 (0.32)	1.32 (0.34)	0.75
P_{max}/mass (W/Kg)	44.1 (11.1)	44.7 (12.9)	0.49	40.6 (5.5)	40.4 (5.0)	0.71
P_{max} left (W)	1.48 (0.58)	1.52 (0.64)	0.23	0.66 (0.16)	0.66 (0.17)	0.61
P_{max} right (W)	1.54 (0.59)	1.58 (0.65)	0.37	0.66 (0.18)	0.67 (0.17)	0.82
pP_{max}/mass (%)	93.3 (13.3)	94.4 (16.2)	0.53	112.4 (13.2)	111.8 (11.5)	0.69
V_{max} (m/s)	2.42 (0.42)	2.44 (0.42)	0.46	2.28 (0.16)	2.26 (0.17)	0.44
Heel-Rise Test[a]						
F_{max} (kN)	1.11 (0.26)	1.14 (0.30)	0.12	0.48 (0.16)	0.49 (0.17)	0.71
F_{max}/BW	1.67 (0.11)	1.72 (0.14)	0.10	1.58 (0.10)	1.59 (0.09)	0.94
P_{max} (W)	0.53 (0.16)	0.58 (0.22)	0.10	0.25 (0.11)	0.25 (0.11)	0.96
P_{max}/mass (W/Kg)	7.80 (1.56)	8.49 (1.76)	0.09	6.90 (1.26)	6.76 (1.09)	0.74
V_{max} (m/s)	0.62 (0.09)	0.66 (0.10)	0.11	0.57 (0.08)	0.56 (0.07)	0.82
Chair-Rise Test						
F_{max} (kN)	1.13 (0.39)	1.17 (0.38)	0.33	0.51 (0.13)	0.52 (0.13)	0.64
F_{max}/BW	1.68 (0.21)	1.74 (0.27)	0.23	1.59 (0.14)	1.64 (0.13)	0.39
P_{max} (W)	0.97 (0.38)	0.95 (0.39)	0.48	0.43 (0.14)	0.43 (0.14)	0.79
P_{max}/mass (W/Kg)	14.3 (4.1)	13.8 (3.9)	0.26	12.9 (2.2)	13.2 (2.8)	0.75
V_{max} (m/s)	1.17 (0.26)	1.12 (0.25)	0.11	1.08 (0.16)	1.09 (0.19)	0.77

[a]N= 12 in the children group, as one participant had invalid results due to a technical problem. The P value indicate the difference between the first and second session.

Table 4. Mean (SD) results of 'speed tests' in two separate test sessions.

	Adults (N = 15)		Children (N = 13)	
	CV (%)	**ICC(C,1) (95% CI)**	**CV (%)**	**ICC(C,1) (95% CI)**
Multiple Two-Legged Hopping				
F_{max}	8.7	0.82 (0.54 to 0.94)	5.7	0.95 (0.83 to 0.98)
F_{max}/BW	7.5	0.73 (0.36 to 0.90)	5.4	0.72 (0.30 to 0.90)
Multiple One-Legged Hopping - Left Leg[a]				
F_{max}	4.8	0.89 (0.68 to 0.96)	5.9	0.94 (0.82 to 0.98)
F_{max}/BW	5.2	0.46 (-0.07 to 0.79)	6.4	0.68 (0.23 to 0.89)
Multiple One-Legged Hopping - Right Leg				
F_{max}	3.7	0.86 (0.62 to 0.95)	4.7	0.96 (0.87 to 0.99)
F_{max}/BW	3.8	0.72 (0.34 to 0.90)	4.2	0.90 (0.69 to 0.97)

[a]N= 14 in the adult group, as one participant had invalid results due to a technical problem.

Table 5. Reliability measures for each parameter in 'force tests'.

	Adults (N=15)		Children (N=13)	
	CV (%)	ICC(C,1) (95% CI)	CV (%)	ICC(C,1) (95% CI)
Single Two-Legged Jump				
F_{max}	6.0	0.76 (0.37 to 0.92)	12.7	0.94 (0.84 to 0.98)
F_{max}/BW	6.6	0.49 (-0.06 to 0.81)	13.1	0.80 (0.50 to 0.93)
F_{max} left	10.4	0.45 (-0.11 to 0.79)	28.5	0.88 (0.67 to 0.96)
F_{max} right	6.7	0.71 (0.29 to 0.90)	13.4	0.92 (0.78 to 0.97)
Jump Height	4.8	0.80 (0.47 to 0.93)	5.0	0.97 (0.91 to 0.99)
P_{max}	5.5	0.98 (0.94 to 0.99)	3.6	0.98 (0.95 to 0.99)
P_{max}/mass	5.5	0.93 (0.79 to 0.98)	3.4	0.96 (0.88 to 0.99)
P_{max} left	5.8	0.95 (0.85 to 0.99)	5.3	0.98 (0.94 to 0.99)
P_{max} right	5.5	0.96 (0.89 to 0.99)	4.8	0.98 (0.95 to 0.99)
pP_{max}/mass	5.0	0.91 (0.73 to 0.97)	3.4	0.90 (0.72 to 0.96)
V_{max}	1.8	0.89 (0.69 to 0.97)	2.3	0.99 (0.96 to 1.00)
Heel-Rise Test[a]				
F_{max}	5.7	0.95 (0.86 to 0.98)	3.3	0.97 (0.92 to 0.99)
F_{max} /BW	4.7	0.62 (0.17 to 0.85)	3.7	0.39 (-0.18 to 0.76)
P_{max}	16.5	0.79 (0.48 to 0.92)	12.7	0.91 (0.73 to 0.97)
P_{max}/mass	13.5	0.62 (0.17 to 0.85)	13.4	0.26 (-0.32 to 0.70)
V_{max}	9.6	0.63 (0.20 to 0.86)	10.5	0.26 (-0.32 to 0.70)
Chair-Rise Test				
F_{max}	8.3	0.94 (0.83 to 0.98)	7.0	0.92 (0.75 to 0.97)
F_{max}/BW	7.9	0.71 (0.32 to 0.89)	7.9	0.10 (-0.46 to 0.60)
P_{max}	8.1	0.96 (0.88 to 0.99)	14.0	0.81 (0.49 to 0.94)
P_{max}/mass	8.0	0.92 (0.79 to 0.97)	15.6	0.31 (-0.26 to 0.72)
V_{max}	6.2	0.93 (0.81 to 0.98)	10.5	0.56 (0.35 to 0.84)

[a]N= 12 in the children group, as one participant had invalid results due to a technical problem.

Table 6. Reliability measures for each parameter in 'speed tests'.

No systematic test-retest differences were found for any of the tests. The CVs of the proposed main outcome parameters for four of the five tests – F_{max}/BW for the M2LH, F_{max}/BW for the M1LH, P_{max}/mass for the S2LJ, F_{max}/BW for the HRT – ranged from 3.4% to 7.5%. However, the main outcome parameter of the CRT (P_{max}/mass) was more variable (CV of 8.0% in adults and 15.6% in children).

In contrast to the CVs, the ICCs varied widely. This is due to the fact that ICCs reflect whether a subject maintains his or her rank within the study population between sessions and thus is influenced by the spread of values found within a study population[19]. Even though studying the rank of subjects within the study population was not one of the aims of the present study, we nevertheless provide results for ICCs, as these values are universally presented in reproducibility studies in sports and rehabilitative sciences.

Many factors contribute to test variability, including device-related, subject-related, and – when tests require the intervention of an observer, observer-related factors. Observer-related factors were minimized in this study, as all test procedures were superintended by the same observer at both time points. The post-acquisition analysis of the signal captured from the force platform was performed automatically by a software program that required minimal user input, with the exception of identifying 'inadmissible' countermovement during the HRT (see Methods section).

Device-related variability was evaluated with repeated static force measurements. When calibrated weights were used, the CVs were below 0.3% for the force range from 196 to 687 N. Repeated testing of the weight of four subjects standing on the platform simultaneously resulted in a CV of 0.09% at a force of close to 3000 N. The F_{max} measurements obtained for the various tests in this study ranged from 271 N (HRT in a girl with a body mass of 17.1 kg) to 4830 N (M2LH in a man with a body mass of 69 kg). Thus, it appears that in the range of peak forces that were encountered in this study, device-related variability probably makes a very small contribution to the overall variability of the result. However, it should be noted that device-related variability was assessed only for force measurements. Whether the device-related variability is similarly low for measures of power and speed was not assessed.

Regarding the accuracy of static force measurements, the device used in this study systematically overestimated forces in the range from 98 N to 686 N by about 0.7%. Accuracy was not determined for higher forces, as the combined weight of all available calibrated weights was 686 N. Although systematic bias is undesirable in any measurement, the bias observed here appears small when compared to the overall variability of the measurements. In addition, the proposed main outcome parameter of each test consists of a ratio between the absolute test result and the subject's body weight or mass. This will cancel out the effect of systematic bias in the absolute results of force measurements.

It is thus likely that the bulk of the test-retest variability that was observed in this study was caused by subject-related variability. A wide variety of factors are likely to contribute to subject-related variability, such as the ability and willingness to follow instructions, motivation or intraday variability. One might hypothesize that children might produce more variable test results than adults, but in fact we found quite similar CVs in the adult and children groups for most of the tests.

The CVs that we found in the present study are similar to those reported in other studies. Reproducibility studies for countermovement jumps to maximal height (corresponding to the S2LJ in our study) yielded CVs for P_{max}/mass of 2.9% for healthy elderly women[20], 3.0% in elite Australian Rules Football players[21], 2.3% in male university students[22], and 3.6% in healthy adults of both sexes aged 19 to 86 years[23], whereas the corresponding CVs in the present study were 5.5% in adults and 3.4% in children.

For maximal bilateral hopping tests (corresponding to our M2LH) Rantalainen et al found CVs for F_{max} of 6.8% in young men and women and of 5.5% in elderly men[12,24], whereas the corresponding CVs in our study were 7.5% in young adults and 5.5% in children. We are not aware of reproducibility studies on the other tests that we have evaluated here.

It is intuitive to assume that variability will be higher for tests that have a more complex movement pattern. The CRT was the most complex test that was evaluated in this series and the variability of the main outcome parameter was higher than for the other tests, especially in children. To obtain more satisfactory reproducibility in the CRT, it may be necessary to modify the test protocol. For example, it might be useful to use a bench with adjustable height[25]. Performing a single sit-to-stand movement might also make the task less complex and thus decrease variability.

No systematic test-retest differences were found for any of the parameters, suggesting that familiarization with test procedures ('learning effect') played a minor role. Similar observations have previously been made for jump height in the S2LJ, as assessed with different methodologies[26,27].

The main limitation of this study is that only healthy subjects were included. It is expected that the variability of test results will be larger in patients with impaired muscle function. However, testing reproducibility in healthy subjects is a necessary first step in the evaluation of a test. A test that is very variable in healthy subjects is unlikely to yield more precise results in patients that are evaluated by the same test.

In conclusion, the present report describes five mechanographic tests. The main outcome parameters of these tests had low variability on inter-day test-retest assessment. It is therefore justified to further evaluate the utility of these tests in the assessment of muscle function in patient groups.

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