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Original Article

Hylonome

Intra- and inter-rater reliability of jumping mechanography muscle function assessments

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Abstract

Muscle function can be assessed through jumping mechanography, where portable ground reaction force plates collect dynamic information as a subject jumps. The aim of this study was to assess both intra- and inter- rater reliability of jumping mechanography. Ten healthy adults underwent 3 sets of testing (collected by 3 different raters) at two separate sessions, one week apart. They performed a number of tests in each session: multiple one-legged hopping (M1LH; on right and left legs) and single two-legged jumps (S2LJ; with or without arm swing). The S2LJ assessed variables of power per body mass, jump height, velocity and efficiency; whereas, M1LH assessed maximum force per body mass and stiffness. Inter-rater coefficients of variation (CV) were less than 0.6% and 2.6% for the S2LJ and M1LH, respectively, for the primary outcome variables of power/body mass and force/body mass. Analyzing intra-rater results also produced CVs less than 5.3% for all variables. The present study reports that the Leonardo ground reaction force plate system yields reproducible results between sessions, without significant contribution of variability from the test operator. Jumping mechanography is an easy, safe and reliable method for the assessment of lower limb musculoskeletal function.

Keywords: Reproducibility, Muscle Function, Mechanography, Force, Power

Introduction

The principal function of muscle is to produce forces which cause motion or maintain posture. This function is achieved by adjusting the length and tension of the muscle. Muscle function is affected by several factors, including lack of physical activity, old age, various musculoskeletal conditions, as well as many chronic diseases. When evaluating physical performance to assess muscle function, it is important to have accurate measuring tools providing data with high reproducibility.

Force platforms are instruments that measure the ground reaction forces generated by a body standing or moving that may be used to indirectly assess various parameters of muscle function of the lower limbs. Force platforms should be distinguished from pressure measuring systems that, although they too quantify centre of pressure, do not directly measure the applied force vector. Therefore, the data from a standing jump on a ground reaction force plate alone are sufficient to calculate acceleration, work, power, and jump distance using basic physics. This technique known as jumping mechanography has become a preferred method to investigate the kinetic parameters (i.e. mechanical power) of lower limb muscle function in both children and adults[1]. Jumping mechanography with the commercially available Leonardo Mechanograph® Ground Reaction Force Plate (GRFP), has been used previously in a number of cross-sectional clinical settings to observe the effects of various factors on muscle function[1-5].

To establish a test for clinical research use, particularly in longitudinal studies, it is important to determine the reliability of the assessment method. Veilleux and Rauch[6] previously reported inter session reproducibility by a single rater of 5 different mechanographic tests, but there has yet to be a report of inter-rater reliability with this system. As the tests are administered by a human rater there is potential variation in the test explanation despite a standardized protocol. In addition, the participant may perceive encouragement differently with different raters. The aim of the present study was to assess the reproducibility of common jumping mechanography tests as

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observed by three different raters at two different sessions using the Leonardo Mechanograph® GRFP.

Methods

Measurement equipment

All tests were performed on the Leonardo Mechanograph® GFRP (Novotec Medical GmbH, Pforzheim, Germany). The force platform is composed of two symmetrical force plates that separate the platform into a left and a right half. Each force plate contains four strain gauge force sensors that measure the vertical ground reaction forces exerted on the platform. The resonance frequency of each plate is 150Hz. The signal from the sensors is sampled at a frequency of 800Hz via USB 2.0 connection to a laptop computer running the Leonardo Mechanograph® GRFP Research Edition Software (version 4.1). The sum of the forces on all the sensors provides measurements of the body mass and force and the plate calculates acceleration (force/mass), as well as velocity through acceleration and subsequently power through velocity[7]. The device was calibrated prior to use each day by a consistent user independent of the three raters evaluated in this study.

Accuracy and precision of static force measurements

In order to ensure the accuracy and precision of the static properties of the force plate, a specific weight test was conducted, as described in detail by Veilleux and Rauch[6]. Briefly, combinations of 10 kg and 20 kg weights were applied to the force plate in different locations. Accuracy (mean difference) and precision (coefficient of variation) were computed at each weight. Additionally, four adult subjects were measured standing on the plate simultaneously. These tests demonstrated that the force plate maintained accurate and precise static force measurements.

Study population

Ten healthy adults (6 male; 4 female; age range 19-35, mean weight [SD] 70.96 [14.7] kg) took part in this study. Adult participants were employees or friends of the Children's Hospital of Eastern Ontario in Ottawa, Canada. Participants were excluded if they reported any musculoskeletal disorder or lower limb bone fracture in the previous six months. Participants provided informed consent. This study was approved by the Research Ethics Board of the Children's Hospital of Eastern Ontario.

Test procedures

Three operators were trained to use the device to collect the data. They utilized the same script with each participant, following the same cues and keywords as described in the individual tests described below. Prior to each assessment, the operator provided each subject with a description of the procedure and a physical demonstration of the test. The subject was allowed to practice the jump once. Before each subject was assessed, as well as in between each trial, the Leonardo Mechanograph® platform was adjusted to read a mass of zero kilograms. After stepping on the device (without shoes), the subject would begin in a neutral position with one foot on each side of the platform. The subject's body mass was recorded and following a single tone, the participant performed one of the test procedures described below. The participants were asked to perform four different jump types, and each was performed three times. They first completed a single two-legged jump (S2LJ) countermovement with static arms (hands on hips) and a S2LJ with freely moving arms. This was followed by right and left multiple one-legged hopping (M1LH).

Weight (N)	Deviation (%)	Max deviation (%)	CV (%)
98.1	0.37 (0.006)	1.4	0.61
196.1	0.30 (0.004)	1.0	0.43
294.2	0.27 (0.004)	1.0	0.49
392.3	0.25 (0.004)	0.9	0.43
490.4	0.23 (0.004)	0.7	0.43
588.4	0.30 (0.004)	0.8	0.40
686.5	0.24 (0.004)	0.7	0.39

Table 1. Results of static force measurements using calibrated weights. Weight: calculated as mass x 9.807 N/kg; Deviation: (measurement result – actual weight) / (actual weight); Max deviation: largest deviation of a single force measurement from the actual weight; CV: coefficient of variation of 12 force measurements at each weight.

Single two-legged jump (S2LJ)

The S2LJ is a vertical jump starting from an erect standing position with allowance for counter-movement with the purpose of achieving maximum height[8,9]. This type of jump has been shown to be the most reliable and valid test for power output of the lower limbs[10]. This was performed two ways, the first with hands fixed on the hips and second with arms moving freely. Arm swing has been shown to positively increase the jump height and both methods are reported throughout the literature[9,11,12]. The operator instructed each participant to jump as high as possible after hearing the tone and to stay still on the plate after the jump until hearing the second beep to conclude the trial. The participant performed one jump per trial and each trial was repeated three times; however, only the jump with the highest height within each trial was used for further analysis. The most important outcome parameter of this test is the maximum power output during the lift off of the jump phase normalized to the body mass of the participant (maximum power/body mass). Also reported are jump height, velocity and efficiency of the motion. Efficiency is a parameter calculated by the device using Power and Acceleration measured during the jump. In human locomotion it is desirable to achieve a certain power with the smallest force necessary to create the most efficient movement/muscle function (i.e. efficiency is greater when less force is used to achieve the same power output). Maximum relative force (max acceleration/g) in healthy subjects during the two-legged jump has been found to be constant at 2.4 g. The formula used by the device to calculate efficiency therefore is Power/kg / (Relative force / 2.4 g)[6,13].

	Rater 1		Rater 2		Rater 3	
	Session 1 (mean±stdev)	Session 2 (mean±stdev)	Session 1 (mean±stdev)	Session 2 (mean±stdev)	Session 1 (mean±stdev)	Session 2 (mean±stdev)
Body weight (kg)	71.21±14.84	70.96±14.73	71.19±14.71	71.12±14.81	71.12±14.66	71.16±14.84
Single two legged jump static arms						
Jump Height (m)	0.36±0.08	0.37±0.11	0.38±0.10	0.37±0.10	0.36±0.09	0.38±0.11
Maximum power/ body mass (W/kg)	41.91±9.62	41.94±10.99	41.96±9.79	41.90±11.18	42.22±9.44	42.15±10.02
Maximum velocity (m/s)	2.32±0.36	2.39±0.38	2.39±0.37	2.40±0.41	2.38±0.36	2.42±0.36
Efficiency (%)	79.63±10.23	86.72±9.03	81.92±11.1	84.39±10.26	85.21±8.66	89.79±10.88
Single two legged jump with arm swing						
Jump Height (m)	0.42±0.10	0.43±0.12	0.43±0.12	0.43±0.11	0.43±0.11	0.44±0.11
Maximum power/ body mass (W/kg)	47.21±10.72	46.62±11.89	46.92±11.66	47.14±11.74	46.94±10.88	47.00±11.35
Maximum velocity (m/s)	2.52±0.36	2.53±0.43	2.54±0.41	2.55±0.41	2.55±0.40	2.54±0.38
Efficiency (%)	88.92±12.57	94.26±9.4	91.91±14.18	96.14±10.29	94.14±10.06	94.87±11.33
Multiple one legged hop						
Maximum force/ body mass (Right) (N/kg)	3.16±0.52	3.03±0.57	3.01±0.45	3.00±0.53	3.02±0.51	3.01 ± 0.51
Maximum force/ body mass (Left) (N/kg)	2.94±0.53	3.00±0.50	2.97±0.58	2.98±0.51	2.83±0.65	2.92±0.52
Stiffness Right (kN/cm)	0.16±0.05	0.16±0.03	0.16±0.03	0.16±0.03	0.18±0.09	0.17±0.03
Stiffness Left (kN/cm)	0.15±0.04	0.16±0.04	0.16±0.03	0.16±0.04	0.17±0.06	0.17±0.04

Table 2. Mean and standard deviation (stdev) results of body weight and mechanographic tests from 10 participants in two sessions collected by three different raters.

Multiple one-legged hop (M1LH)

The maximal ground reaction forces observed during the M1LH can be used to determine the maximum force. The M1LH is also widely used to assess the leg stiffness, a useful parameter in the design of training regimes or rehabilitation programs[14].

The participants completed three right leg M1LH trials, and then repeated the procedure on their left leg. They were asked, upon hearing an audible tone, to raise one leg and jump on the forefoot of the other, keeping the knee of their jumping leg straight, to prevent movement of the knee joint. Participants started with smaller hops to establish rhythm, and were then encouraged to jump "stronger" until five to eight hops were observed, without their heel touching the ground. The computer software automatically selected the hop with the greatest force and eliminated any invalid ones (as in when the heel was recorded touching the ground). The operator manually verified that all selections and omissions were valid. The most important outcome parameter of this test is the maximum force generated normalized to the body mass of the participant (maximum force/body mass). We also report on stiffness, which represents the average overall stiffness in the integrated musculoskeletal system during the ground-contact phase. Generally, when one hops in place, the stiffness of the leg is altered to increase hopping frequency or hopping height. The calculation of stiffness is described in detail in Ferris and Farley[15].

Statistical analysis

Statistical analysis was performed using SPSS (v. 20, SPSS Inc. Chicago Il, USA). ANOVA was used to investigate the measurement outcomes across the three raters and between the two sessions. Two measures of reproducibility were calculated, coefficient of variation (CV) and intraclass correlation coefficient (ICC). CVs, defined as the standard deviation divided by the mean of the observations, were computed to allow comparison with other reports on the repeatability and reproducibility of muscle function assessments. CVs are also useful to look at pure measurement variability, as in the static force measurements using calibrated weights. Intraclass correlation describes how strongly measurements in the same group resemble each other. Intraclass correlation operates on data structured as groups, rather than data structured as paired observations. A model 3 (two-way mixed, consistency) single measure ICC was used in this study. In the mixed model, the participant is treated as a random effect, whereas measurement error is considered as a fixed effect[16]. Thus, ICC(2,1) and their 95% confidence intervals are reported.

Results

To assess accuracy, static weight measurements were performed in the range from 98.1N to 686.5N. The maximal deviation from the reference weights in any of the 84 static measurements performed in this study was 1.4% (accuracy) (Table 1). The CV for the 12 repeated measurements was 0.61% for the smallest weights used in this study (98.1 N), and 0.24% for the larger weights (686.5 N). Twelve separate weight measurements of four adult subjects who stood on the platform simultaneously were also measured to determine pre-

	Session 1		Session 2	
	CV (%)	ICC (95% CI)	CV (%)	ICC (95% CI)
Single two legged jump with static arms				
Jump Height	3.1%	0.831 (0.602 to 0.950)	0.6%	0.984 (0.956 to 0.996)
Maximum power/ body mass	0.4%	0.970 (0.914 to 0.992)	0.3%	0.984 (0.954 to 0.996)
Maximum velocity	1.6%	0.906 (0.761 to 0.973)	0.6%	0.981 (0.948 to 0.995)
Efficiency	3.4%	0.711 (0.389 to 0.908)	3.1%	0.792 (0.499 to 0.938)
Single two legged jump with arm swing				
Jump Height	1.1%	0.828 (0.586 to 0.950)	1.8%	0.951 (0.870 to 0.986)
Maximum power/ body mass	0.3%	0.911 (0.766 to 0.975)	0.6%	0.990 (0.971 to 0.997)
Maximum velocity	0.5%	0.947 (0.857 to 0.985)	0.4%	0.987 (0.962 to 0.996)
Efficiency	2.8%	0.658 (0.319 to 0.888)	1.0%	0.912 (0.774 to 0.975)
Multiple one legged jump				
Maximum force/ body mass (Right)	2.5%	0.950 (0.804 to 0.988)	0.6%	0.979 (0.941 to 0.994)
Maximum force/ body mass (Left)	2.6%	0.578 (0.196 to 0.857)	1.4%	0.971 (0.918 to 0.992)
Stiffness Right	6.8%	0.375 (-0.021 to 0.759)	3.2%	0.659 (0.316 to 0.889)
Stiffness Left	3.7%	0.809 (0.560 to 0.943)	2.0%	0.741 (0.429 to 0.920)

Table 3. Coefficient of variation (CV) and intraclass correlation coefficient (ICC) results comparing data from the inter rater investigations (within a session), shown separately for the inter-rater assessment during session 1 and session 2.

cision at higher force levels. This produced an average weight measurement of 2572.83 N +/- 1.73N, resulting in a CV of 0.07%. The inter-day variability of weight measurements within our study population was 0.1% (see Table 2 for absolute measurements). Table 2 provides an overview of a subset of parameters for each jump on session 1 and session 2. These values represent means of all subjects collected by each rater. There was no significant difference between sessions or raters for any outcome measure ($p<0.001$).

Reliability and reproducibility measures for the jumps assessed by 3 different raters (inter-rater reliability) at two time points are presented in Table 3. The S2LJ, which has been shown to assess velocity and power[17], had parameters of power/body mass and maximum velocity with the lowest CVs (0.3-4.3%, depending on the session) and the highest ICCs (0.906-0.991). Efficiency and jump height had higher CVs, with the highest CV (3.4%) in the S2LJ without arm swing (session 1). The M1LH results followed similar trends, with low CVs and generally high ICCs in the force parameters. Stiffness had slightly higher CVs and lower ICCs between raters in each session; however, still within the acceptable reproducible range.

Table 4 describes the variability between the sessions for each rater (intra-rater reliability). Power/body mass and maximum velocities produced with the S2LJ had very low CVs between sessions (0.1% to 0.9% depending on rater and hand position); whereas, efficiency had slightly more variability with CVs ranging between 2.1% and 6.0%. The M1LH had CVs ranging from 0.3% to 2.8% for maximum force per body mass, as well as generally high ICCs for the force parameters. Maximum force per body mass produced the highest ICCs on the right side (0.958 to 0.989). Stiffness saw slightly higher CVs and lower ICCs, particularly right-sided stiffness between sessions.

Discussion

In the present study we describe variations of two mechanographic tests that are currently in use to assess the muscle function of the lower limbs. As an assessment of their validity in repeated observations, we evaluated inter-rater reliability and inter-session reproducibility (intra-rater reliability) of jumping mechanography with the Leonardo GRFP. These data are important, as it is essential to have access to accurate measurement methods to properly determine the longitudinal effects of disease (i.e. rheumatological conditions) or intervention (i.e. biological anti-inflammatory medications) on physical performance. Our reported primary outcome parameters for the S2LJ of jump height, velocity, and power (Table 2) are similar to those adult values previously reported in the literature[6,18].

The reliability results presented here do not show any systematic test-retest differences in the main outcome variables for the mechanographic tests investigated (Tables 3 and 4). The CVs of the outcome parameters measured for both the S2LJ (with and without arm swing) and M1LJ were all under 6%. In contrast to CVs, the ICCs had slightly more variability. This is due to the fact that ICCs are influenced by the spread of values found within a study population. Although we were not studying the rank of the subjects within the study population in this report, we documented ICCs as they are often presented in test re-test reliability studies in sports and applied biomechanics. For example, we measured stiffness from the M1LH and determined that although the means were generally consistent (Table 2), and that CVs fell within an acceptable range, the ICCs for two of the comparisons were below 0.5. This suggests care should be taken when interpreting small changes in an individual's stiffness measurement.

For the primary outcome variables of force and power per body mass, the measures of reproducibility reported in this study are similar or lower than those reported in other studies. A previous reliability report with the Leonardo system presented CVs between 1.8 and 5.5%[6] for parameters comparable to those presented here; however, they did not look at efficiency (S2LJ) or stiffness (M1LH), two parameters that showed the most variability in our study. Interestingly, both efficiency and stiffness are measured indirectly (unlike muscle

	Rater 1		Rater 2		Rater 3	
	CV	**ICC (95% CI)**	**CV**	**ICC (95% CI)**	**CV**	**ICC (95% CI)**
Single two legged jump – hands on hips						
Jump Height	2.3%	0.696 (0.151 to 0.915)	1.1%	0.919 (0.712 to 0.979)	3.5%	0.871 (0.586 to 0.966)
Maximum power/ body mass	0.1%	0.949 (0.819 to 0.987)	0.1%	0.931 (0.761 to 0.982)	0.1%	0.945 (0.807 to 0.986)
Maximum velocity	2.0%	0.782 (0.362 to 0.940)	0.3%	0.913 (0.690 to 0.978)	1.1%	0.953 (0.835 to 0.988)
Efficiency	6.0%	0.525 (-0.063 to 0.854)	2.1%	0.562 (-0.055 to 0.870)	3.7%	0.786 (0.188 to 0.947)
Single two legged jump – arm swing						
Jump Height	0.4%	0.905 (0.662 to 0.976)	0.5%	0.831 (0.447 to 0.955)	1.5%	0.863 (0.546 to 0.964)
Maximum power/body mass	0.9%	0.981 (0.931 to 0.995)	0.3%	0.888 (0.609 to 0.971)	0.1%	0.966 (0.871 to 0.992)
Maximum velocity	0.1%	0.936 (0.763 to 0.984)	0.1%	0.908 (0.671 to 0.976)	0.4%	0.930 (0.745 to 0.982)
Efficiency	4.1%	0.443 (-0.135 to 0.818)	3.2%	0.515 (-0.087 to 0.850)	0.5%	0.774 (0.310 to 0.939)
Multiple one legged jump						
Maximum force/body mass (Right)	2.8%	0.958 (0.565 to 0.992)	0.4%	0.962 (0.855 to 0.990)	0.3%	0.989 (0.957 to 0.97)
Maximum force/body mass (Left)	1.4%	0.805 (0.395 to 0.948)	1.5%	0.721 (0.184 to 0.924)	2.2%	0.645 (0.059 to 0.899)
Stiffness Right	2.4%	0.514 (-0.164 to 0.855)	0.8%	0.774 (0.307 to 0.939)	4.7%	0.293 (-0.436 to 0.767)
Stiffness Left	5.3%	0.780 (0.363 to 0.939)	1.8%	0.726 (0.210 to 0.925)	2.0%	0.910 (0.690 to 0.977)

Table 4. Coefficient of variation (CV) and intraclass correlation coefficient (ICC) results comparing data from the intra rater (between sessions) for three different raters.

force), and calculated from the parameters directly measured during the jump. These measurements are of potential interest in the characterization and analysis of an individual's muscle function. Efficiency is a parameter that informs a global assessment of muscle function and human locomotion. From a conceptual point of view, the use of as little force as possible to achieve a certain power is not only desirable to save energy, but also to avoid excess forces that could cause damage and wear on multiple structures. The calculation of efficiency therefore might provide interesting additional information beyond the measurement of peak power. Efficiency was recently introduced to the set of calculated measurements available on the Leonardo device and to our knowledge, has yet to be applied in published trials. It is also a parameter that was directly developed by the manufacturer based on theoretical considerations, not existing literature. We nevertheless feel that it might provide useful additional information and the assessment of interrater reliability is an important first step before reporting efficiency in clinical trials.

Stiffness is based on the spring-like feature of the human muscle during hopping. The concentric and eccentric phase of muscle contractions, as well as energy storage are influenced by the stiffness of the muscle. For example, in a clinical situation of pain in one extremity, the stiffness of the muscle is often increased affecting the muscle function. This parameter is based on the work of Farley et al who described the term whole body stiffness, or leg stiffness in animals, as well as in humans[19-21]. Pediatric normative data for stiffness have recently been published[22]. While the variability observed for both efficiency and stiffness necessitates caution in interpreting the results, they remain potentially important parameters in research and clinical applications.

Other systems have been tested in the same fashion. For example, the Myotest-T accelerometry system for the measurement of vertical jump height in male basketball players has shown high session to session reproducibility (ICCs 0.92-0.96)[23]. Similarly, Optojump photoelectric cells for estimating vertical jump height had high ICCs (0.98) and low coefficients of variation (2.7%)[24]. Other reproducibility studies for countermovement jumps, corresponding to the single two legged jump in our study, yielded consistently high ICCs[9,25] with CVs between 4 and 6%[25,26] for jump height between sessions on different days. Our corresponding CVs for jump height ranged from 0.4-1.5% depending on the rater. As noted above, there have been numerous reliability studies associated with the single two-legged jump and generally the systems and key variables have been deemed reproducible, similar to the report here. The present study not only investigates the two-legged jump, but also reports on the variability associated with the multiple one-legged hop of which there are fewer comparable reports in the literature.

Test variability can be influenced by many factors, including biological variability, instrumentation, error by the subject, and error by the operator. Each trial is composed of the true measurement and error. Error is typically considered as being two types: systematic error, including bias and constant error, as well as random error, otherwise known as imprecision. Constant error affects all scores equally, whereas bias is systematic error that affects certain scores differently than others. In testing of physical performance, subjects may improve their scores simply due to learning effects, e.g. the performance of the first test serves as practice for the subsequent tests, or fatigue may result in poorer performance across trials. We could speculate that there was a small learning effect in our study with the M1LH, where CVs from session 1 were halved in session 2 (Table 3). In contrast, random error refers to sources of error that are due to chance factors, such as luck, alertness, and normal biological variability. Such errors should, in a random manner, both increase and decrease measurement scores on repeated testing. It is likely that the majority of the acceptable test-retest variability observed in this study is due to the intra-individual variability. However, given that there is high correlation between two sessions for a given rater, then the measurement system has good test-retest reliability for our primary outcome variables.

Instrument related variability was evaluated with repeated static measurements. CVs were below 0.6% when calibrated weights were used to produce forces between 98 N and 687 N, the. Repeated testing of the weight of four subjects standing on the platform simultaneously resulted in a CV less than 0.1% at forces above 2500 N. The maximum forces achieved in this study from specific participants ranged between 1300 N and 3100 N (M1LH). Thus from our accuracy and precision results, it can be inferred that device-related variability makes a relatively small contribution to the overall reliability of the results.

This, to our knowledge, is the first report of inter-rater reliability with the Leonardo GRFP system. Inter-rater reliability estimates within and between each measurement occasion were found to be very good, and similar findings were seen when the data were stratified by rater. This suggests that very little variability in the measurements came from the rater, and that a single rater measurement is sufficient. Although the raters were trained to collect these data with a script, the Leonardo GRFP system is simple and can easily be learned and applied. This is particularly important when using this technique to assess the influence of disease process or intervention on muscle function with repeated observations at given time intervals.

The present study reports outcome parameters from jumps performed using the Leonardo GRFP mechanographic system. All of the tests investigated had primary outcome variables with low variability on both inter-day test-retest assessment and inter-rater reliability. However, this study was performed with healthy participants from a sample of convenience, it is possible that functionally impaired populations may yield more variable results. Like others[26], we suggest that reliability in muscle function assessments is a critical factor in the ability of tests to determine changes in physical capabilities over time and that scores may be dependent on the method of assessment. With appropriate population specific tests, we propose that this system could be of value in the muscle function assessment of patient groups in longitudinal studies.

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