J Musculoskelet Neuronal Interact 2012; 12(4):219-223

Original Article

Hylonome

Agreement between vertical ground reaction force and ground reaction force vector in five common clinical tests

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Abstract

Mechanography is an innovative method to evaluate lower-limb dynamic muscle function. This technique is generally performed on force platforms that measure only the vertical component of ground reaction force (GRF). The underlying assumption is that medio-lateral and antero-posterior forces do not contribute significantly to the GRF in jumping and rising tests. The goal of this study was to establish the validity of this assumption. Fifteen healthy adults (mean age [SD]: 30 [11] years; mean height [SD]: 1.68 [0.12] m; mean body mass: 70 [18] kg) performed three repetitions of five different tests in the following order: multiple two-legged hopping, multiple one-legged hopping, single two-legged jump, heel-rise test and chair-rise test. An excellent agreement was found between peak GRF and peak vertical GRF. In each of the five tests, peak vertical GRF represented more than 99% of peak GRF. Moreover, the limits of agreement ranged between 0.05% (multiple two-legged hopping test) and 0.4% (heel-rise test) of the averaged peak force measurements. Therefore measuring only the vertical component of ground reaction force in healthy participants is appropriate for the five tests used in the present study.

Keywords: Mechanography, Ground Reaction Force, Muscle Function, Agreement, Clinical Tests

Introduction

Mechanography is a method to assess dynamic lower-limb muscle function through the measurement of ground reaction force (GRF)[1,2]. The technique is easily applicable to clinical environments[2-4] and provides meaningful outcomes in assessing muscle function in pediatric, geriatric and healthy populations[1,2,4]. Depending on a subject's functional status or the scientific goal that is sought, one or several of the following five tests are used: (1) Multiple one-legged hopping; (2) multiple two-legged hopping; (3) single two-legged jump; (4) chair-rise test; (5) the heel-rise test.

Multiple one-legged and two-legged tests consist of performing ten hops without touching the ground with the heel. These two hopping manoeuvres estimate maximum voluntary muscle force in the lower leg[5]. Because of these maximal forces, both multiple hopping tests are well suited to assess the muscle-bone interaction[4,5].The single two-legged jump is a vertical countermovement jump to achieve maximum jump height. This test is used because it is highly representative of movements produced by children and athletes in everyday life. Also, in contrast with the hopping tests where muscle force is the most relevant parameter, the single two-legged jump provides a measure of muscle power. Measuring power is suitable to quantify muscle function in some specific populations such as in elderly persons[2] for which muscle power is decreasing much more importantly than force during the aging process[6]. The chair-rise test is a classical sit-to-stand test with five repetitions. The rationale for using this test is that it is highly representative of everyday life movements, it is a good predictor of falls and fractures[7,8] and it is used to determine the gross functional level of an individual[9]. Finally, the heel-rise test consists of five bilateral heel rises performed as fast as possible. This test was introduced because it could be also performed by patients who are unable to jump or who are unable to rise from sitting position[10].

The authors have no conflict of interest.

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Edited by: J. Rittweger
Accepted 23 November 2012

In addition to the clinical rationale, there are also physiological reasons to use different tests. For example, both hopping tests and the single two-legged jump require the production of a stretch-shortening cycle i.e., an eccentric contraction quickly followed by a concentric one[11]. In contrast, the heel-rise test requires a pure concentric contraction whereas the chair-rise test is a complex combination of different muscle contractions[12]. Therefore, from a physiological point of view mechanographic assessments cover a wide range of muscle contractions.

In order to simplify the measurement process, mechanography is usually performed on a portable force platform that measures only the vertical component of GRF (vGRF)[1,2,13,14]. The assumption underlying this approach is that medio-lateral and antero-posterior forces do not contribute significantly to the GRF in these tests. However, it is unclear at present what error is introduced by this simplifying assumption. Some of the tests may lead to disturbances in balance and thus could result in the production of medio-lateral and antero-posterior forces. In that case, the sole measurement of the peak vGRF may lead to an underestimation of the maximal forces applied to the force platform. Therefore, the goal of the present study was to assess the level of agreement between vGRF and GRF in five different mechanographic tests More specifically, we intended to determine whether the ground reaction force is significantly underestimated when only the vertical component of the ground reaction force is taken into account when non-physically impaired participants perform mechanographic tests.

Subjects and Methods

Fifteen healthy adults (mean age [SD]: 30 [11] years; mean height [SD]: 1.68 [0.12] m; mean body mass: 70 [18] kg; 7 males) took part in this study. Participants were recruited from hospital staff, research staff and students. This study was approved by the ethics committee of the Sainte-Justine University Hospital Research Center and all participants provided informed consent prior to testing.

Measurement equipment

vGRF (Fz), as well as anterior-posterior (Fy) and medial-lateral (Fx) components of GRF were measured using a quadratic (50 cm x 50 cm) portable force platform (AMTI, Watertown, USA). The signal from the force sensors was sampled at 400 Hz.

Test procedure

The force platform was placed on a solid floor and adjusted according to the manufacturer procedure to remove any offset load before each trial. For each participant, the experimenter provided a standardized description of the procedure and demonstration of the task. The participant then stood on the device in an upright position, with feet placed at shoulder width. Following a single-tone pitch, the participant performed one of the test manoeuvres and thereafter remained still for at least 2 seconds. The termination of the test was indicated by a double-tone pitch. Three valid trials were performed for each test. Depending on the test, a trial was defined as a single jump (for the single two-legged jump) or as a series of 5 (heel-rise test and chair-rise test) or 10 consecutive vertical up-and-down movements (multiple two-legged and multiple one-legged hopping). The correct execution of each trial was visually assessed by an experienced experimenter (LNV). The trial with the highest peak force was retained for analysis. The jump and rise tests were performed in the following order: multiple two-legged hopping, multiple one-legged hopping, single two-legged jump, heel-rise test, and chair-rise test. A detailed description of the five tests is provided elsewhere[10].

Data analysis

Raw force plate data were filtered using a second-order Butterworth low-pass filter (cutoff frequency: 20 Hz) and the GRF vector was calculated. For the single two-legged jump, two maximal GRFs were defined; one during the takeoff phase and the other during the landing phase. For the other tests, only the maximal value of the takeoff phase was retained. For each selected trial, maximal values of the GRF and of the vGRF were selected. Within each test, the differences between peak vGRF and peak GRF were assessed by computing the percent difference between these two values for each participant. Individual percentages were subsequently averaged for a given test. Data filtering and analysis was done using a customized Matlab program (The Mathworks, Natick, USA).

To determine the correspondence between GRF and vGRF over the entire duration of each jump and rise tests, the root mean square error (RMSE) between Fz(t) and F(t) curves were computed:

$$(1)\ RMSE = \sqrt{\frac{\sum_{i=1}^{\alpha} (Fz_i - F_i)^2}{\alpha}}$$

Where i represents each sample, Fz is the vertical ground reaction force, F is the ground reaction force vector and a the number of samples.

Statistical analysis

Results are presented as mean (SD). To determine whether peak vGRF is in agreement with peak GRF, Bland and Altman plots and limits of agreement analyses were calculated[15] using SPSS 17.0 (IBM, Chicago, USA).

Results and Discussion

On average, for the five tests assessed in the present study peak vGRF represented 99.8%±0.2% of peak GRF (Table 1). This observation implies negligible contribution of the horizontal GRF components measured at peak GRF. Also, the limits of agreement (see Figure 1) represented 0.05% (multiple two-legged hopping test) to 0.4% (heel-rise test) of the averaged peak force measurements, indicating good agreement between the two methods. RMSE values (Table 1) of the force-time curves comparison represented between 1 and 2% of mean GRF measured throughout a whole specific test. This indicates that the correspondence between the vGRF and the GRF vector remained high

	GRFmax (N)	vGRFmax (N)	%Δ	RMSE (N)
Multiple one-legged hopping (left)	2089 (447)	2087 (446)	0.1 (0.1)	4.7 (3.8)
Multiple one-legged hopping (right)	2049 (408)	2047 (408)	0.1 (0.1)	5.2 (4.4)
Multiple two-legged hopping	3199 (679)	3197 (679)	0.1 (0.1)	6.4 (4.7)
Single two-legged jump (takeoff)	1598 (343)	1594 (342)	0.2 (0.2)	3.5 (1.3)
Single two-legged jump (landing)	2625 (656)	2619 (656)	0.3 (0.2)	
Heel-rise test	1771 (597)	1763 (595)	0.4 (0.3)	2.4 (0.6)
Chair-rise test	1082 (284)	1078 (283)	0.4 (0.3)	2.1 (0.9)

Data are presented as mean (SD).

Table 1. Peak GRF (GRFmax), peak vGRF (vGRFmax), percent difference and the root mean square error of the force/time curves comparison.

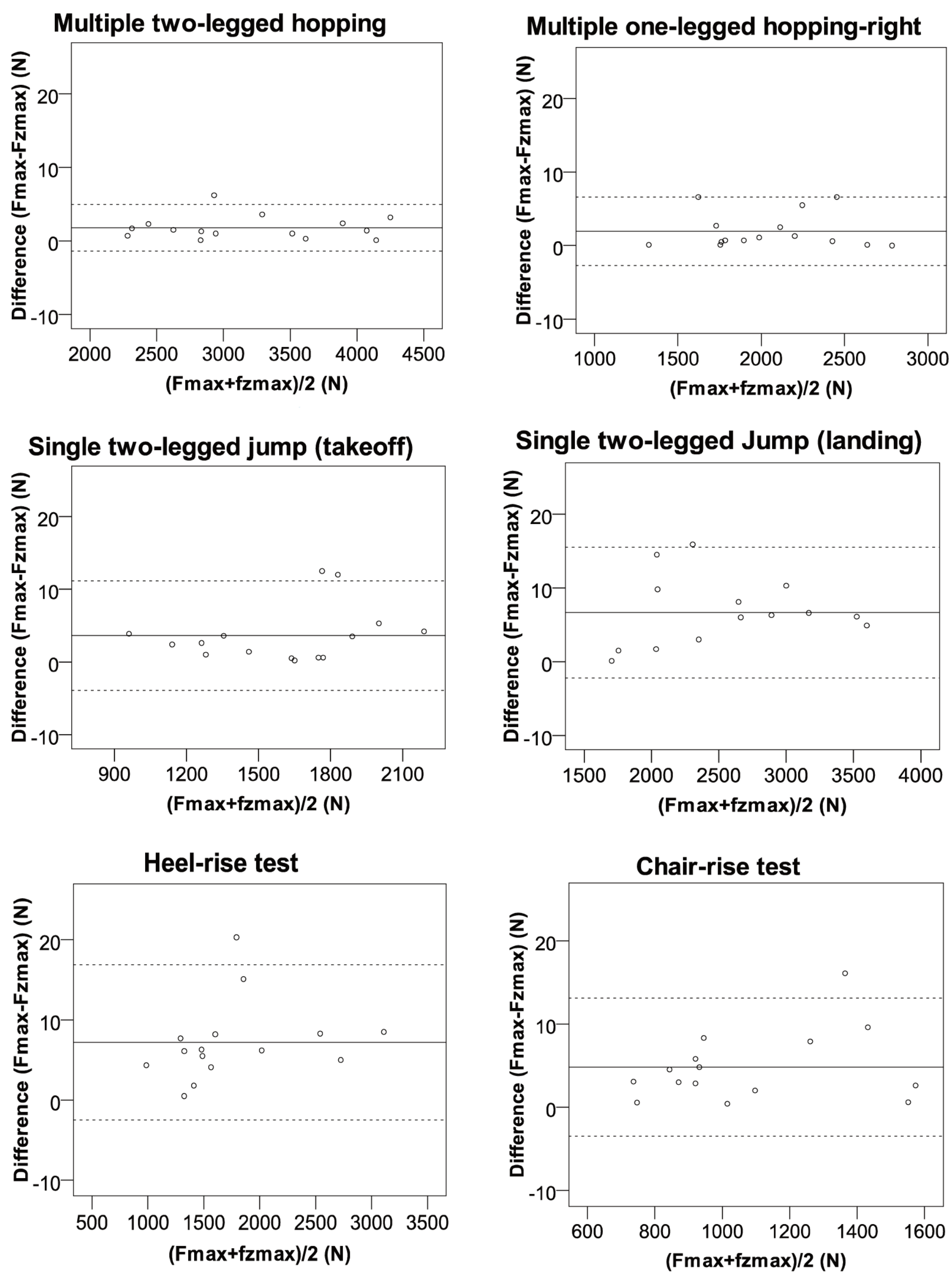

Figure 1. Bland and Altman plots depict the differences between peak GRF (Fmax) and peak vGRF (Fz max) against the average values (filled lines), with 95% limits of agreement (broken lines) for each of the five clinical tests.

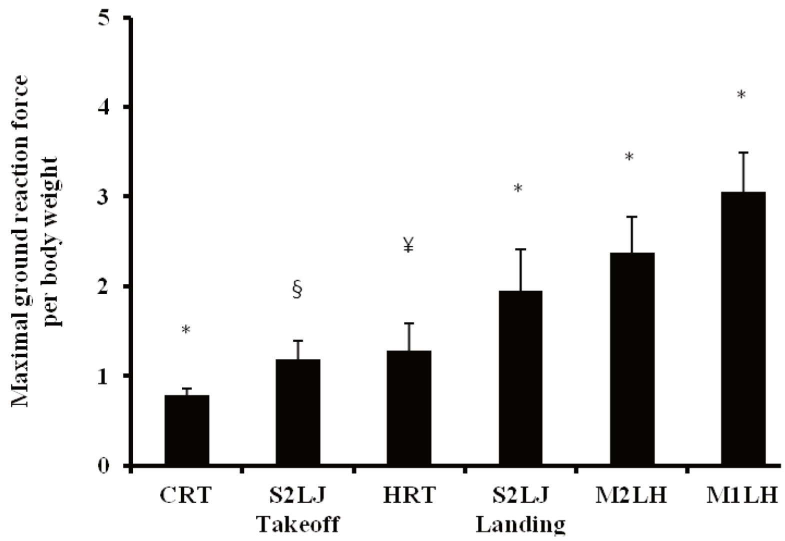

Figure 2. Comparisons of peak GRF per leg (Fmax) for each of the five clinical tests. CRT: Chair-rise test; S2LJ: single two-legged jump; HRT: heel-rise test; M2LH: multiple two-legged hopping; M1LH: multiple one-legged hopping.* Significantly different from the other values ($p<0{,}01$); § Significantly different from the other values, except heel-rise test ($p<0.01$); ¥ Significantly different from the other values, except single two-legged jump-takeoff ($p<0.01$).

for the whole duration of the test, or put in other words that the horizontal components of the GRF vector were negligible at all time during the tests. In turn, this suggests that measuring only the vertical component of the GRF is sufficient to assess muscle function, even in tests involving some horizontal displacement such as the single two-legged jump and the chair-rise test.

The three most relevant parameters assessed by mechanography are peak force, peak power and peak velocity. In this study we focused on peak ground reaction forces. This parameter is highly relevant for multiple one-legged and two-legged hopping tests as such tests are known to induce the maximal ground reaction force. However, single-two legged jump, chair-rising test and heel-rising test are most appropriate to provide a measure of muscle power and velocity[10]. In mechanography, power and velocity are computed from ground reaction force measurements and they are therefore both likely to be influenced by its horizontal components. The problem is that peak power and peak velocity are unlikely to occur at the same time as peak force. To overcome this problem, we measured the root mean square error of the force-time curves (vertical GRF vs. GRF vector) throughout the whole test duration. The low values of RMSE, less than 2% of the average force measurement for each of the five tests, suggest that vertical GRF were in agreement with GRF vector not only at peak force but throughout the whole test. In turn this indicates that force-derived parameters (power and velocity) are unlikely to be influenced by the horizontal components of the GRF.

In conclusion, the five mechanographic tests can be performed by determining only the vertical component ground reaction force in healthy participants, as the difference to the GRF vector is minimal.

Supplementary notes

In addition to the main goal of the present study, we report the maximal force applied on one leg during the different tests (Figure 2). Such information is of interest in clinical environments because a close relationship exists between peak ground reaction force (especially forefoot ground reaction forces) and the force applied on the lower limb's bones during such tests[5]. For the test involving two legged ground contact (i.e.: Chair-rise test, single two-legged jump, heel rise-test, multiple two-legged jump) we assumed that the ground reaction force was equally distributed between the two legs and data were therefore divided by two. Statistical analysis was performed using a one-way repeated ANOVA followed by Bonferroni test for multiple group comparisons.

As it can be seen on Figure 2, multiple one-legged hopping test yielded the highest maximal vertical ground reaction force per bodyweight. Looking more specifically into the three tests isolating plantar flexor muscles (i.e., heel rise, two- and one-legged hopping tests) maximal vertical ground reaction forces were respectively 30% and 57% lower in the multiple two-legged hopping and heel-rise than in the one-legged hopping test.

Acknowledgements

This study was supported by the Shriners of North America, The Fonds de la Recherche en Santé du Québec, the Réseau Provincial de Recherche en Adaptation-Réadaptation (REPAR) as well as the MENTOR and the MEDITIS program supported by the Canadian Institutes of Health Research and the Natural Sciences and Engineering Research Council of Canada, respectively. The sponsor had no involvement what so ever with regard to the content of the present manuscript. We would like to thank Roshni Alam for her assistance with study procedures.

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