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Original Article

Validity of an accelerometer as a vertical ground reaction force measuring device in healthy children and adolescents and in children and adolescents with osteogenesis imperfecta type I

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Abstract

Introduction: Vertical ground reaction forces (vGRFs) are closely related to bone strength and development. It is therefore relevant to assess these forces in bone disorders accompanied with muscle weakness such as in osteogenesis imperfecta type I (OI type I). The purpose of the present study was to assess the validity of vGRFs derived from an accelerometer. **Methods:** Fourteen children and adolescents with a diagnosis of OI type I (age range: 7 to 21; mean age [SD]: 14.1 [4.8] years; 5 males) and fourteen healthy controls (age range: 6 to 21; mean age [SD]: 12.5 [4.2] years; 5 males) performed three repetitions of five different jump and rise tests on a ground reaction force plate. Jumps and rises outcomes were measured simultaneously with the ground reaction force plate and an accelerometer. **Results:** Pearson correlation coefficients were over 0.96 ($p<0.001$) for the five tests. The limits of agreement represented between 17 and 31% of the average peak force measured by both devices. The accelerometer is a promising tool to assess ground reaction forces in everyday life settings and has been shown to be sufficiently sensitive to detect muscular weakness in children and adolescent with OI type I.

Keywords: Accelerometer, Vertical Ground Reaction Forces, Agreement, Osteogenesis Imperfecta, Healthy Children and Adolescents

Introduction

Accelerometers have become increasingly popular to assess physical activity in free-living conditions. They are often used to estimate the energy expenditure and has been extensively validated in this respect[1-4]. However, the accelerometer remains little investigated with regard to measuring vertical ground reaction forces (vGRFs). Measuring this parameter is important in bone disorders as it relates to the mechanical loading of the skeleton which strongly influences bone development and regulation[5].

Osteogenesis imperfecta (OI) is a heritable disorder characterized by low bone mass and increased bone fragility that is usually caused by mutations in one of the two genes that encode collagen type I, *COL1A1* and *COL1A2*[6]. OI type I is the mildest and most common form of the disorder[7]. Children and adolescents with OI type I typically have few functional limitations but sometimes have muscular weakness of unclear etiology[8-10]. In that context, using a simple device like an accelerometer would be highly valuable for the assessment of vGRFs and thereof the mechanical loading of the bones. This is especially true for a population with a bone disorder presenting muscle weakness such as in OI type I.

vGRFs can be easily estimated from raw acceleration profiles through the second Newtonian law of motion (Force= mass X acceleration). Therefore, in addition to quantifying energy expenditure, accelerometers could be used as a ground reaction force measuring device in free living condition. Re-

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lationships between counts (a common accelerometer outcome variable) and vGRFs measured by a ground reaction force plate have been investigated[11-13] but the definition of 'counts' varies between accelerometer brand and the relationships are task-specific[12].

A few studies have assessed the direct relationship between vGRFs measured by a force plate and an accelerometer[14-16]. Only one of these studies was done in a pediatric population[14]. Accelerations and vGRFs were measured in thirty-five 12 to 14 years old adolescents during walking and running. The authors showed that vGRFs correlate well (r^2=0.97; p<0.001) with actual vGRFs measured with a ground reaction force plate.The results of this study suggest that this approach is valid for the investigation of sustained and repetitive activities such as walking and running. However, although walking and running typify a fair proportion of children's everyday life, another important proportion of these activities consists in the production of short bursts of physical activity such as those observed during vertical jumping or chair-rising[17]. These high intensity actions are known to generate high peak forces at a high rate i.e., generally lasting less than 1s. As noted by Neugebauer and colleagues[14], one important limitation of their study is that peak resultant acceleration was averaged over a relatively long period of time (15s epoch length). This averaging method is unlikely to efficiently capture the transient aspect of jumping and rising maneuvers.

Therefore, in the present study we suggest a simple approach in which instant acceleration data are converted into vGRFs through the second Newtonian law of motion[16]. This approach has shown its potential in healthy adult and elderly populations, although it has not yet been investigated in typically developing children and in children with musculoskeletal disorders. Healthy children and adolescents as well as children and adolescents with OI type I were asked to perform five different jump and rise manoeuvres on a portable force platform while wearing an accelerometer on the right hip. The selected multiple two-legged hopping, the multiple one-legged hopping, the single two-legged jump, the heel-rise and the chair-rise tests have been validated in healthy children and adolescents[18] and in children and adolescent with OI type I[10]. The specific goal of this study was to assess the validity of vGRFs measurements derived from raw accelerometer data in a variety of actions that closely represent movements occurring in children's everyday life[17] and requiring production of short but high bursts of force. The selected tests have been shown to cover a large range of vGRFs[19].

Participants and methods

Study population

Fourteen children and adolescents with a diagnosis of OI type I (age range: 7 to 21; mean age [SD]: 14.1 [4.8] years; 5 males) took part in this study. Patients were recruited at the Shriners Hospital for Children in Montreal. Patients were excluded if they had any fracture or surgery in the lower limb in the past twelve months. Fourteen healthy children and adolescents (age range: 6 to 21; mean age [SD]: 12.5 [4.2] years; 5 males) also took part in this study. Healthy participants were recruited among unaffected siblings of patients (i.e., not presenting clinical signs of OI), and children of hospital employees. This study was approved by the Institutional Review Board of the Faculty of Medicine of McGill University. Informed consent was provided by participants or, in minors, by their parents. Assent was provided by participants aged 7 to 17 years.

Measurement equipment

Accelerometer. The GT3X+ accelerometer (Actigraph™, LLC, Pensacola, FL, USA) was used to measure acceleration in three dimensions (vertical, antero-posterior and medio-lateral). The GT3X+ weighs 19 g and its dimensions are 4.6 cm (height) X 3.3 cm (width) X 1.5 cm (thick). The acceleration data was sampled by a 12 bit analog to digital converter at rates ranging from 30Hz to 100Hz and stored in a raw, non-filtered format in the units of gravity (g's). The largest acceleration detectable by the device is 6 g. In this study, the data were recorded at a frequency of 60 Hz and were downloaded in raw format to a laptop with the Actilife 6.0 software through a USB cable.

Force Plate. The Leonardo Mechanograph® Ground Reaction Force Plate (Leonardo Mechanography GRFP, Novotec Medical Inc., Pforzheim, Germany) was used to measure vertical ground reaction forces[18,19]. The signal from the force sensors was sampled at a frequency of 800 Hz and was analyzed using the Leonardo Mechanography GRFP Research Edition® software (Leonardo Mechanography GRFP Research Edition Software, version 4.2-b05.53-RES; Novotec Medical).

Height was measured using a Harpenden stadiometer (Holtain, Crymych, UK). Body mass was determined using the portable force platform Leonardo Mechanography GRFP.

Test procedure

The experimenter carefully positioned the accelerometer on the patient's right waist slightly behind the anterior iliac crest[4]. The device was held in place directly on the participant's skin with an elastic band.

Prior to each test, the experimenter provided a description of the procedure and a physical demonstration of the task to the participant. The force platform was adjusted to indicate a mass of zero kg before a participant stepped onto it. The participant stood on the device in an upright position with their arms relaxed on their sides, one foot on each side of the platform at shoulder width. Body mass was recorded once the participant stood still for at least 2 seconds. Following a single-tone pitch, the participant performed the test manoeuvre. After each trial, the participant remained still for at least 2 seconds. A double-tone pitch indicated the end of the test.

Participants were asked to perform five different tests in the following order: multiple two-legged hopping, multiple one-legged hopping, single two-legged jump, heel-rise test, chair-rise test, as described in detail elsewhere[18]. Three valid trials were performed for each test. A trial was defined as a single

	Control	OI type I	P
Gender (M/F)	5/9	5/9	
Age (years)	12.5 (4.2)	14.1 (4.8)	0.37
Height (cm)	152.4 (21.6)	150.1 (17.3)	0.76
Body Mass (kg)	48.7 (17.8)	47.9 (20.9)	0.92

Results are shown as mean (SD).

Table 1. Anthropometric data.

	Control	OI	Δ%
Multiple Two-Legged Hopping[a]			
GT3X	4.73 (0.76)	3.83 (0.56)	-24
Leonardo GRFP	4.63 (0.79)	3.88 (0.49)	-20
Multiple One-Legged Hopping-Right Leg[b]			
GT3X	2.95 (0.39)	2.26 (0.27)	-30
Leonardo GRFP	3.07 (0.43)	2.50 (0.26)	-23
Multiple One-Legged Hopping-Left Leg[b]			
GT3X	3.22 (0.52)	2.56 (0.23)	-26
Leonardo GRFP	3.02 (0.48)	2.44 (0.23)	-24
Single Two-Legged Jump			
GT3X	2.43 (0.48)	2.29 (0.30)	-6
Leonardo GRFP	2.20 (0.23)	2.13 (0.21)	-3
Heel-Rise Test			
GT3X	1.43 (0.19)	1.39 (0.10)	-3
Leonardo GRFP	1.50 (0.16)	1.45 (0.10)	-3
Chair-Rise Test[c]			
GT3X	1.49 (0.19)	1.39 (0.12)	-7
Leonardo GRFP	1.57 (0.14)	1.43 (0.17)	-10

Results are shown as mean (SD). GT3X: Accelerometer data; Leonardo GRFP: force plate data; Significant differences between groups: [a]$p=0.003$; [b]$p<0.001$; [c]$p=0.04$.

Table 2. Peak force measurements relative to body weight in patients and control participants as a function of the tests and the measuring device.

jump (for the single two-legged jump) or as a series of 5 movements (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. At the end of the first test session, the accelerometer was given back to the experimenter and the data were downloaded to a laptop.

Data analysis

To assess validity and reproducibility of the GT3X+ for the measurement of vertical ground reaction forces, raw vertical accelerations were transformed into force with the following formula:
(1) vGRFs $(kN) = |((a\ (g) * 9.807\ (m/s^2)) * BM\ (kg)) / 1000|$.
where a is the instant acceleration and BM is the body mass of the participant.

To determine validity of the GT3X+ as a force-measuring device, the highest force value of each of the three trials for each of the five tests were used for further statistical analyses.

Statistical analyses

To assess validity, Pearson correlation between data recorded by the GT3X accelerometer and the ground reaction force plate was established for comparison to similar studies[12,13]. Bland and Altman plots and limits of agreement were calculated for each group and for each of the five tests to determine the level of agreement between the accelerometer and the ground reaction force plate measurements[20]. Bland and Altman analyses were performed on each group independently. It may be assumed that OI patients do not engage in the same kind of physical activities as do their healthy peers due to fear of fracture and higher fracture risks. Therefore, OI children may not have the same level of expertise as healthy children due to their lack of practice. As a result, jumping movement

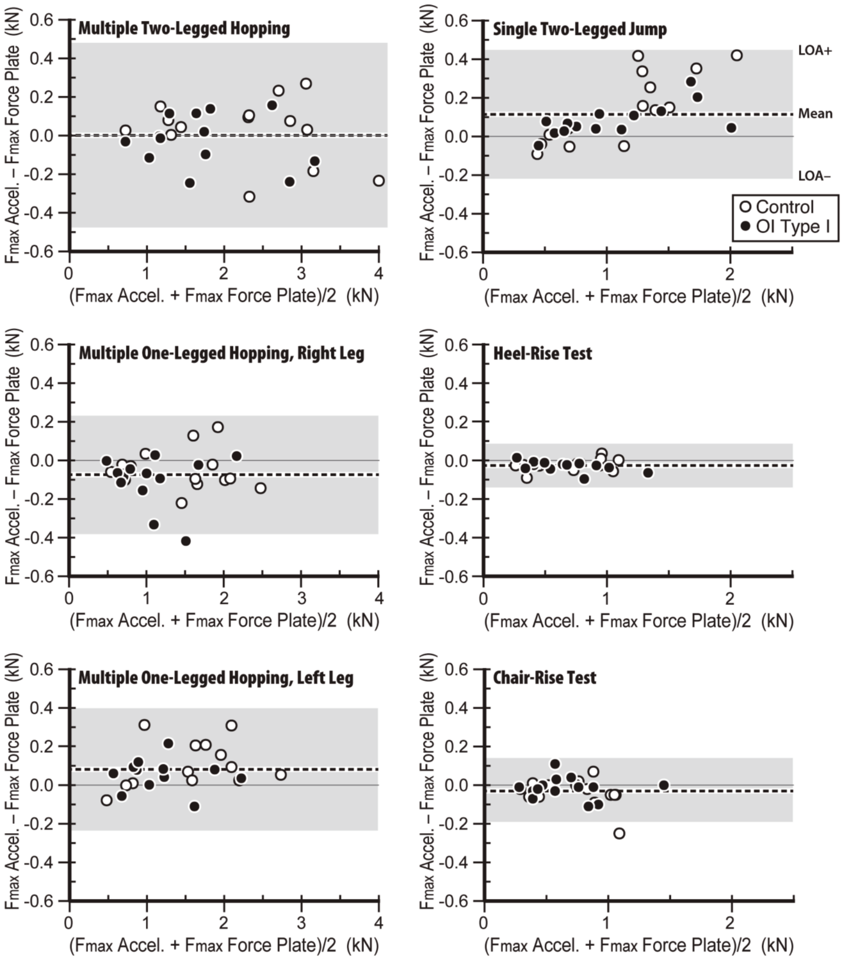

Figure 1. Bland and Altman plots showing the differences between peak ground reaction forces (Fmax; kN) as measured by the GT3X Accelerometer and the Leonardo Ground Reaction Force Plate against the average values (doted line), with 95% limits of agreement (grey shadow) for each of the five clinical tests. Black circles represent data of participants with OI type I and white filled circles represent data of control participants.

patterns may differ between OI patients and controls. This could lead to increased instability at the trunk which in turn may influence recordings due to increased medio-lateral and antero-posterior ground reaction force production.

Peak force of three consecutive trials was kept for this analysis. Therefore, the Bland and Altman method for repeated measurements was used[21]. Heteroscedasticity was present in one test (S2LJ), that is, the absolute differences were correlated with the magnitude of the mean (R<0.05). Under this circumstance, it is suggested that data should be log transformed to remove this relationship. Therefore, data of both systems were (natural) log transformed and the standard approach was then applied on these data. However, this procedure did not allow removing the relationship and therefore the normal approach was used. An ANOVA contrasting two groups (Control vs. OI type I) and two devices (accelerometer vs. force plate) with repeated measures on the last factor was computed to detect any systematic difference between groups and devices on absolute peak force and peak force relative to body weight[18]. All statistical analyses were performed using PASW 18® (SPSS Inc., Chicago, IL, USA). The *p* values are set at 0.05.

Results

Patients with OI type I did not differ from healthy participants with regard to age, height and body mass (Table 1). One patient was unable to generate enough force to perform both multiple one-legged hopping tests (i.e. on the right and left foot) whereas another patient could not perform the multiple one-legged hopping on the left foot for the same reason. The ANOVA with peak force relative to body weight set as the dependent variable (Table 2) revealed that patients with OI produced significantly lower forces than healthy participants for the multiple one-legged ($p<0.001$) and two-legged hopping ($p=0.003$) tests as well as for the chair-rising test ($p=0.04$), regardless of the device used for force recordings. No differences were found for the single two-legged jump and for the heel-rise test on both devices.

	GT3X	Leonardo GRFP	Δ%
Multiple Two-Legged Hopping			
Healthy	2.28 (0.93)	2.25 (0.97)	1
OI type I	1.72 (0.73)	1.75 (0.75)	-1
Multiple One-Legged Hopping-Right Leg[a]			
Healthy	1.44 (0.61)	1.49 (0.62)	-3
OI type I	1.02 (0.48)	1.13 (0.48)	-9
Multiple One-Legged Hopping-Left Leg[b]			
Healthy	1.58 (0.69)	1.48 (0.66)	7
OI type I	1.22 (0.50)	1.16 (0.50)	5
Single Two-Legged Jump[b]			
Healthy	1.20 (0.57)	1.06 (0.42)	14
OI type I	1.09 (0.53)	1.01 (0.48)	8
Heel-Rise Test[a]			
Healthy	0.70 (0.29)	0.72 (0.28)	-3
OI type I	0.65 (0.30)	0.68 (0.31)	-4
Chair-Rise Test[d]			
Healthy	0.72 (0.27)	0.76 (0.30)	-5
OI type I	0.65 (0.30)	0.67 (0.31)	-2

Results are shown as mean (SD). GT3X: Accelerometer data; Leonardo GRFP: force plate data; Significant differences between measuring devices [a]p=0.003, [b]p=0.001, [c]p<0.001, [d]p=0.04.

Table 3. Absolute peak force measurements (kN) in patients and control participants as a function of the tests and the measuring device.

The results of the Bland and Altman analyses, more specifically the limits of agreement presented in percent of the average force measurements, were similar between groups and were as follows: Multiple two-legged hopping: 26% vs. 33%; multiple one-legged hopping of the right leg: 25 vs. 26%; multiple one-legged hopping-left leg: 22 vs. 23%; single two-legged jump: 36 vs 23%; heel-rise test: 16 vs 15% and chair-rise test 28 vs. 20%, respectively for the healthy participants and OI patients. Therefore, we decided to pool all data for simplicity sake. The Bland and Altman plots (Figure 1) illustrate the agreement between force measurements derived from the accelerometer and those collected by the ground reaction force plate. The limits of agreement represented 24% of the average peak force measured by both devices for the multiple two-legged hopping, the multiple one-legged hopping on the right leg and the chair rise test and 23% 31%, 17% for the multiple one-legged hopping on the left leg, the single two-legged jump and the heel-rise test, respectively. Correlation coefficients between peak ground reaction force measured by the accelerometer and the GRFP were of: 0.97 (Multiple two-legged hopping), 0.96 (Multiple one-legged hopping-Left leg), 0.97 (Multiple one-legged-Right leg), 0.96 (Single two-legged jump, Heel-rise test), 0.99 (Chair-rise test; all p's<0.001)

The ANOVA (Table 3) comparing the averaged peak force of the accelerometer to those of the ground reaction force plate showed that the accelerometer in both groups significantly underestimated the forces measured by the force plate by 6% in the multiple one-legged hopping on the right foot (p=0.003), and by 4% in the heel-rise test (p<0.001) and the chair-rise test (p=0.04) but significantly overestimated these by 6% in the multiple one-legged hopping test on the left foot (p=0.04) and by 11% in the single two-legged jump (p=0.001). For the multiple two-legged hopping there was no observable overestimation or underestimation of the forces by the accelerometer (p=1).

Discussion

This study on children and adolescents with OI type I and on healthy participants shows moderate to good agreement between forces derived from an accelerometer and those measured by a ground reaction force plate during the execution of five different manoeuvres. Importantly, however, the observed differences in vGRFs between the OI type I group and the control group were very similar with the two devices.

Previous studies have reported close correlations, between vGRFs measured by a force platform and accelerometer derived vGRFs during a heel-rising test (r=0.98)[16], vertical jumping (r=0.90)[15] and walking and running (r^2=0.97)[14]. The high correlations reported in the current study are similar to that observed in those previously stated studies and concur to suggest that measuring vGRFs with an accelerometer is a highly valid approach in children and adolescents. However, correlation analysis is a statistically inadequate way to establish agreement between two methods[20]. Correlations reflect the spread of values within a study population and therefore provide information about a specific study population rather than about the methods that are to be compared[22]. They also provide a measure of the strength of the relationship between two variables but fail to specifically measure agreement between these two variables. For example, a perfect correlation could be observed if data points were distributed along any straight line whereas perfect agreement would be observed only if data points were distributed along the line of equality. The Bland and Altman approach has been developed to avoid these pitfalls[20]. Using this approach, we found limits of agreement that were between 16% to 24% of the average force measurements in 5 of the 6 tests and a higher limit of agreement for the single two-legged jump (31%). In our opinion, these results suggest acceptable agreement between the two methods. However, it contrasts with the very high correlations that we and others have reported and highlights the usefulness of the Bland and Altman approach to complement the more traditional correlation approach in validation studies.

Despite some differences in force readings, our data suggests that the accelerometer is a potentially valuable tool to estimate ground reaction forces in everyday life settings. The small over/underestimation of averaged vGRFs by the accelerometer's derived forces suggests that over a long period of recordings (i.e. many repetitions) force measurements are quite accurate. That the accelerometer could reflect vGRFs of everyday life movements accurately is supported by the fact that the tests used in the current study reflect a wide range of ground reaction forces; from 1.3 to 4.7 times body weight[19]. Most importantly, our data indicate that the accelerometer and the force plate found similar differences between the OI type I cohort and the control group. It may be possible to use an accelerometer in studies that compare muscle force between two groups of relatively functional study cohorts with the tests that were evaluated in the present study. Therefore, the accelerometer can be a suitable tool for assessing ground reaction forces during the tests that were evaluated in the present study.

The agreement between the accelerometer and the force plate measurements may be influenced by movement artifacts of the accelerometer, as it is placed directly on the skin[23]. This could explain the accelerometer force overestimation in the multiple one-legged hopping on the left leg and in the single two-legged jump. Positioning the accelerometer on the right hip may have also increased the discrepancy between the two methods, especially during asymmetric movements, such as one-legged hopping[23]. It might have been more appropriate to place the accelerometer at or near the center of mass, i.e. at the lower back[16]. In the current study, we opted for the right hip placement because this site has been extensively validated for the assessment of energy expenditure in home based settings. Finally, it was noted that there was a proportional bias in the single two-legged jump, i.e. that forces were underestimated at low levels of vGRFs whereas they were overestimated at higher levels of vGRFs. This test requires production of pronounced simultaneous hip and trunk flexions and extensions. Because the accelerometer was worn at the hip, it is possible that the velocity at which the extensions occur prior to lift off had an influence on the accelerometer such as displacement artifacts or inclination.

Conclusions

The goal of the present study was to determine if one could use raw acceleration data to computed ground reactions forces in different maneuvers mimicking a fair proportion of children's everyday life activities. High correlations were reported as well as limits of agreement representing on average 20% of the measured forces. In addition, the accelerometer derived data allowed detection of expected significant differences between both study populations. Accelerometry seems to be a valid tool to estimate vGRFs in everyday life settings in typically developing children as well as in children wih OI.

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