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Both a single sacral marker and the whole-body center of mass accurately estimate peak vertical ground reaction force in running

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A R T I C L E I N F O

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A B S T R A C T

Background: While running, the human body absorbs repetitive shocks with every step. These shocks can be quantified by the peak vertical ground reaction force ($F_{v,\max}$). To measure so, using a force plate is the gold standard method (GSM), but not always at hand. In this case, a motion capture system might be an alternative if it accurately estimates $F_{v,\max}$.

Research question: The purpose of this study was to estimate $F_{v,\max}$ based on motion capture data and validate the obtained estimates with force plate-based measures.

Methods: One hundred and fifteen runners participated at this study and ran at 9, 11, and 13 km/h. Force data (1000 Hz) and whole-body kinematics (200 Hz) were acquired with an instrumented treadmill and an opto-electronic system, respectively. The vertical ground reaction force was reconstructed from either the whole-body center of mass (COM-M) or sacral marker (SACR-M) accelerations, calculated as the second derivative of their respective positions, and further low-pass filtered using several cutoff frequencies (2−20 Hz) and a fourth-order Butterworth filter.

Results: The most accurate estimations of $F_{v,\max}$ were obtained using 5 and 4 Hz cutoff frequencies for the filtering of COM and sacral marker accelerations, respectively. GSM, COM-M, and SACR-M were not significantly different at 11 km/h but were at 9 and 13 km/h. The comparison between GSM and COM-M or SACR-M for each speed depicted root mean square error (RMSE) smaller or equal to 0.17BW (≤6.5 %) and no systematic bias at 11 km/h but small systematic biases at 9 and 13 km/h (≤0.09 BW). COM-M gave systematic biases three times smaller than SACR-M and two times smaller RMSE.

Significance: The findings of this study support the use of either COM-M or SACR-M using data filtered at 5 and 4 Hz, respectively, to estimate $F_{v,\max}$ during level treadmill runs at endurance speeds.

1. Introduction

Even though running can offer many health benefits, the incidence of running related injuries remains high [1]. These injuries often occur when the loading of the musculoskeletal system exceeds its load bearing capacities. This loading corresponds to the repetitive shocks associated with every step that the human body must absorb by adopting a specific running biomechanics. Although the magnitude of these shocks are relatively insubstantial, in the order of 1.5–2.5 body weights (BW) for the active peak [2], their quantity can be significant. For instance, an individual running an average of 20 km/week produces more than one million of active peaks during a one year period [3].

Although the internal forces contribute most to the experienced loading [4,5], the external forces are often used as substitute measures to estimate the loading of the musculoskeletal system [5–8]. For instance, moderate correlation was observed between the active peak force, i.e., peak vertical ground reaction force ($F_{v,\max}$), and peak axial tibial compressive force [6]. It was also suggested that the peak tibial

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bone loading occurs during midstance at $F_{v,\max}$ [5,8] and that $F_{v,\max}$ is representative of the magnitude of external bone loading during the stance running phase [5]. For these reasons, $F_{v,\max}$ proved to be one important biomechanical parameter to accurately measure, though this variable alone should not be used to assess running related injuries [9].

The measurement of $F_{v,\max}$ is usually performed using force plates, which is considered as the gold standard method (GSM). However, an instrumented treadmill would be required to conduct such measurement in the laboratory, which could not always be affordable or at hand [10, 11]. In such case, alternatives would be to use a sacral-mounted inertial measurement unit (IMU) [12–15] or a motion capture system [16,17]. The former is low-cost and practical to use in a coaching environment [18] while the latter, though more expensive, allows an in-depth assessment of running kinematics and is the alternative employed in the present study.

Using Newton's second law, which states that the sum of the forces applied to the human body is given by the body mass (m) multiplied by the acceleration of its center of mass (COM), vertical ground reaction force (F_v) can easily be recovered when assuming no air resistance and is given by Eq. 1

$$F_v(t) = m[a_v(t) + g] \tag{1}$$

where mg represents body weight and a_v is the whole-body COM vertical acceleration. The latter is the last piece of missing information in the previous equation and can be provided by the outcome of the motion capture system. Indeed, based on the three-dimensional (3D) kinematics of the entire body, the COM trajectory is computed as a weighted sum of the COM of each body segments (segmental analysis) [19], which ultimately allows obtaining the whole-body COM acceleration by computing the second derivative of the COM trajectory.

Although the segmental analysis is quite widespread, it is not a perfect estimation. For instance, it is subject to soft tissue artefact [20] and relies on accurate markers placement [21]. Moreover, this methods is time-consuming due to the large number of markers required to approximate each segment as a rigid body, where the choice of each rigid body, i.e., the schematic model of each body segment, is essential to correctly estimate the whole-body COM [22]. Furthermore, body segments need to be assigned inertial properties and COM locations based on their shape [23], and attributed relative mass based on standard regression equations [24], which add extra approximations. For these reasons, Napier, Jiang, MacLean, Menon and Hunt [25] approximated the whole-body COM trajectory by the trajectory of a single marker placed on the sacrum at the midpoint of the posterior superior iliac spines. These authors demonstrated that this very simple alternative was a valid proxy for the COM trajectory in vertical and fore-aft directions at specific events of the running cycle [25]. However, to the best of our knowledge, using the vertical acceleration of a single sacral marker to estimate $F_{v,\max}$ has never been investigated while using the whole-body vertical COM acceleration has already been attempted but using a single participant [26].

Alternatively, sacral acceleration directly recorded using sacral-mounted IMU were used to estimate $F_{v,\max}$ [12–15]. For instance, Alcantara, Day, Hahn and Grabowski [13] predicted $F_{v,\max}$ using machine learning and reported a root mean square error (RMSE) of 0.15 BW. Moreover, weak to moderate correlations were obtained between $F_{v,\max}$ measured using GSM and estimated using IMU data [12]. These authors observed an effect of the low-pass cutoff frequency used for the IMU data, where a better correlation was depicted for a 10 Hz than a 5 or 30 Hz cutoff frequency.

The previous findings suggest that the choice of the cutoff frequency proved to be important. Indeed, a substantial filtering method is required to avoid unrealistic peaks in the acceleration signal [19]. However, the effect of the cutoff frequency was not investigated when estimating $F_{v,\max}$ from whole-body COM [26]. Hence, the purpose of this study was to 1) estimate $F_{v,\max}$ based on whole-body COM (COM method; COM-M) and sacral marker (sacral marker method: SACR-M) accelerations filtered using several cutoff frequencies (2−20 Hz), and 2) compare these estimations against GSM at several treadmill speeds. We hypothesized that 1) a single cutoff frequency should minimize RMSE and that this cutoff frequency should be different for each method and 2) a similar RMSE than in Alcantara, Day, Hahn and Grabowski [13] should be obtained, i.e., ~0.15 BW.

2. Materials and methods

2.1. Participant characteristics

Hundred and fifteen recreational runners, 87 males (age: 30 ± 8 years, height: 180 ± 6 cm, body mass: 70 ± 7 kg, and weekly running distance: 38 ± 24 km) and 28 females (age: 30 ± 7 years, height: 169 ± 5 cm, body mass: 61 ± 6 kg, and weekly running distance: 22 ± 16 km) voluntarily participated in this study. For study inclusion, participants were required to not have current or recent lower-extremity injury (≤1month), to run at least once a week, and to have an estimated maximal aerobic speed ≥14 km/h. The study protocol was approved by the local Ethics Committee (CER-VD 2020−00334).

2.2. Experimental procedure

After providing written informed consent, retroreflective markers were positioned on participants (described in Subsec. 2.3 Data collection and processing) to assess their running biomechanics. As for each participant, a 7-min warm-up run was performed on an instrumented treadmill (Arsalis T150 – FMT-MED, Louvain-la-Neuve, Belgium). Speed was set to 9 km/h for the first 3 min and was then increased by 0.5 km/h every 30 s. This was followed, after a short break (<5 min), by a 1-s static trial on the same treadmill for calibration. Then, three 1-min runs (9, 11, and 13 km/h) were performed in a randomized order (1-min recovery between each run). 3D kinematic and kinetic data were collected during the first 10 strides following the 30-s mark of running trials. All participants were familiar with running on a treadmill as part of their usual training program and wore their habitual running shoes.

2.3. Data collection and processing

Whole-body 3D kinematic data were collected at 200 Hz using motion capture (8 cameras) and Vicon Nexus software v2.9.3 (Vicon, Oxford, UK). Forty-three and 39 retro-reflective markers of 12.5 mm diameter were used for static and running trials, respectively. They were affixed to skin and shoes of individuals over anatomical landmarks using double-sided tape following standard guidelines [27]. Synchronized kinetic data (1000 Hz) were collected using the force plate embedded into the treadmill.

3D marker and ground reaction force (analog signal) were exported in. c3d format and processed in Visual3D Professional software v6.01.12 (C-Motion Inc., Germantown, MD, USA). 3D marker data were interpolated using a third-order polynomial least-square fit algorithm (using three frames of data before and after the "gap" to calculate the coefficients of the polynomial), allowing a maximum of 20 frames for gap filling, and subsequently low-pass filtered at 20 Hz using a fourth-order Butterworth filter. 3D ground reaction force signal was filtered using the same filter and downsampled to 200 Hz to match the sampling frequency of marker data.

From the marker set, a full-body biomechanical model with six degrees of freedom and 15 rigid segments was constructed. Segments included the head, upper arms, lower arms, hands, thorax, pelvis, thighs, shanks, and feet. Whole-body COM trajectory was calculated from the parameters of all 15 segments (directly provided by Visual3D). A sacral marker was reconstructed (virtual marker) at the midpoint between the two markers affixed to the posterior superior iliac spines [25]. Noteworthy, similar results would have been obtained by using a real marker at this same location because marker placement error and soft tissue movement artefact are expected to be low in this region (prominence of bony landmarks and lack of soft tissue) [25].

The acceleration of the COM and sacral marker trajectories were calculated by computing their second derivative and were subsequently low-pass filtered using a fourth-order Butterworth filter. Several cutoff frequencies have been tested: 20, 10, 5, 4, 3, and 2 Hz. This choice of cutoff frequencies follows from the fact that any frequency above 20 Hz should arise due to vibration [3] while 3 Hz spike is considered to be reflective of step frequencies (vertical sinusoidal pelvic motion) [28]. For each low-pass filtered acceleration of both COM and sacral marker, the ground reaction force was reconstructed using Eq. 1. Finally, $F_{v,\max}$ was given by the maximum of the measured (GSM) and both estimated (COM-M and SACR-M) vertical ground reaction force signals between foot-strike and toe-off events. These events were identified within visual3D and detected by applying a 20 N threshold to the vertical component of the ground reaction force [29]. The body mass of each participant was obtained from body weight recorded during the static trial and was used in Eq. 1 and to express force-like data in BW. For further analyses, each $F_{v,\max}$ (from GSM, COM-M, and SACR-M) of each participant was given by the average over the 20 consecutive $F_{v,\max}$ values corresponding to the 10 analyzed strides. Errors in estimating $F_{v,\max}$ with respect to GSM using either COM-M or SACR-M were calculated using RMSE (in absolute and relative units, i.e., normalized by the mean $F_{v,\max}$ value over all participants and obtained using GSM). The best cutoff frequency for COM-M and SACR-M was determined as the frequency which minimized RMSE. Statistical analysis was performed on $F_{v,\max}$ estimated by the most accurate COM-M and SACR-M. Data analysis was performed using Python (v3.7.4, available at http://www.python.org).

2.4. Statistical analysis

All data are presented as mean ± standard deviation. Bland-Altman plots were constructed to examine the presence of systematic bias on $F_{v,\max}$ between COM-M and GSM as well as between SACR-M and GSM for each running speed [30,31]. Corresponding lower and upper limit of agreements and 95 % confidence intervals (CI) were calculated. Systematic biases have a direction, i.e., positive values indicate overestimations of COM-M or SACR-M while negative values indicate underestimations. Then, after having inspected residual plots and having observed no obvious deviations from homoscedasticity or normality, two-way [method of calculation (GSM vs COM-M vs SACR-M) x running speed (9 vs 11 vs 13)] repeated measures ANOVA with Mauchly's correction for sphericity and employing Holm corrections for pairwise post hoc comparisons were performed. Differences between GSM, COM-M, and SACR-M were quantified using Cohen's d effect size and interpreted as very small, small, moderate, and large when $|d|$ values were close to 0.01, 0.2, 0.5, and 0.8, respectively [32]. Statistical analysis was performed using Jamovi (v1.2, retrieved from https://www.jamovi.org) with a level of significance set at $P \leq 0.05$.

3. Results

RMSE of the estimation of $F_{v,\max}$ with respect to GSM using either COM-M or SACR-M as function of the cutoff frequency of the fourth-order Butterworth filter is depicted in Fig. 1 for the three running speeds. The filter frequencies which minimized RMSE were 5 and 4 Hz for COM-M and SACR-M, respectively, for the three speeds. RMSE for COM-M with a 5 Hz cutoff frequency at 9, 11, and 13 km/h were 0.06, 0.07, and 0.08 BW, respectively, while RMSE for SACR-M with a 4 Hz cutoff frequency at 9, 11, and 13 km/h were 0.14, 0.13, and 0.17 BW, respectively (RMSE for all cutoff frequencies and running speeds are reported in Table S1). $F_{v,\max}$ estimated by COM-M and SACR-M using these best frequencies were kept for the following analyses.

Fig. 2 depicts the vertical ground reaction force obtained using GSM (force plate) as well as COM-M and SACR-M using data filtered at 5 and 4 Hz, respectively.

No systematic bias was reported for $F_{v,\max}$ at 11 km/h for both COM-M and SACR-M compared to GSM (the zero line lied within the 95 % CI) while small biases were obtained at 9 and 13 km/h [≤0.09 BW (≤61.8 N for a 70 kg person); Fig. 3 and Table 1]. RMSE was smaller or equal to 0.06 BW (≤2.6 %) and 0.17 BW (≤6.5 %) for the comparison between GSM and COM-M and between GSM and SACR-M, respectively (Table 1). Estimations of $F_{v,\max}$ using COM-M and SACR-M in Fig. 3 and Tables 1–3 were obtained using data filtered at 5 and 4 Hz, respectively.

Repeated measures ANOVA depicted significant effects for both running speed and method of calculation x running speed interaction ($P < 0.001$; Table 2) but there was no effect of the method of calculation ($P = 0.41$; Table 2). Holm post hoc tests yielded significant differences between $F_{v,\max}$ obtained using pair of methods at 9 and 13 km/h ($P \leq 0.003$) but not at 11 km/h ($P \geq 0.23$). The other pairwise post hoc comparisons were all statistically significant ($P \leq 0.03$) except the pair GSM at 11 km/h and SACR-M at 13 km/h ($P = 0.23$). Besides, while a linear increase in $F_{v,\max}$ with increasing speed is reported for GSM and COM-M, this is less true for SACR-M (Table 2).

Cohen's d effect sizes were very small for the comparison of each pair of methods at 11 km/h and GSM and COM-M at 9 km/h, small for GSM and COM-M at 13 km/h and COM-M and SACR-M at 9 and 13 km/h, and moderate for GSM and SACR-M at 9 and 13 km/h were moderate (Table 3).

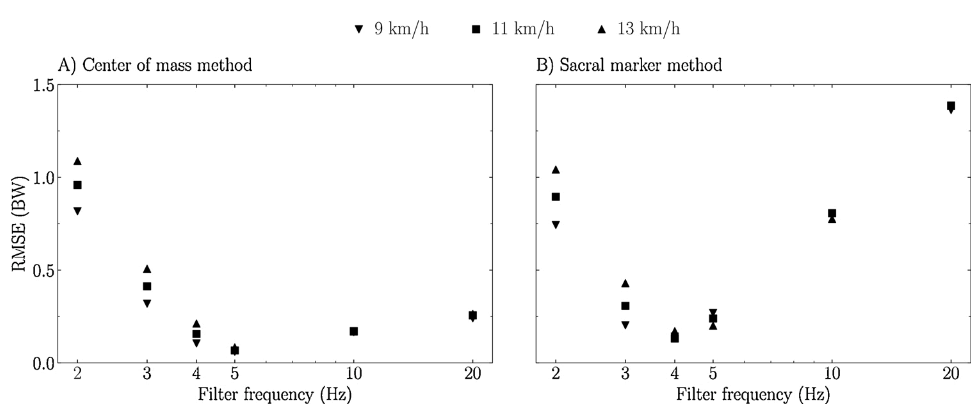

Fig. 1. Root mean square error [RMSE; in body weight (BW)] of the estimation of the peak vertical ground reaction force with respect to the gold standard method using A) the center of mass method (COM-M) and B) the sacral marker method (SACR-M), as function of the cutoff frequency of the fourth-order Butterworth low-pass filter and for three running speeds. Noteworthy, a log-scale was used on the x-axis to improve readability and vertical force was filtered at 20 Hz.

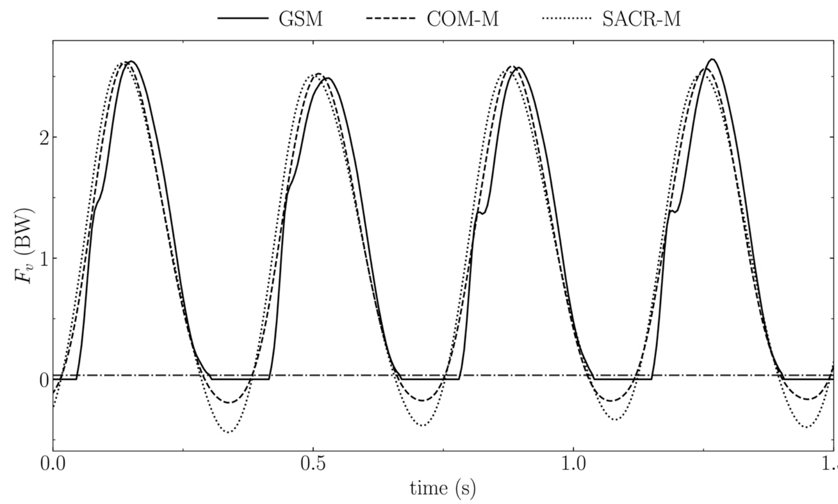

Fig. 2. Vertical ground reaction force [F_v; in body weight (BW)] obtained using force plate and filtered at 20 Hz, i.e., gold standard method (GSM; solid line), center of mass method using a 5 Hz filter (COM-M; dashed line), and sacral marker method using a 4 Hz filter (SACR-M; dotted line) during two running strides for a representative participant at 11 km/h. The gray dash-dotted line represents the 20 N threshold used to detect foot-strike and toe-off events on the GSM.

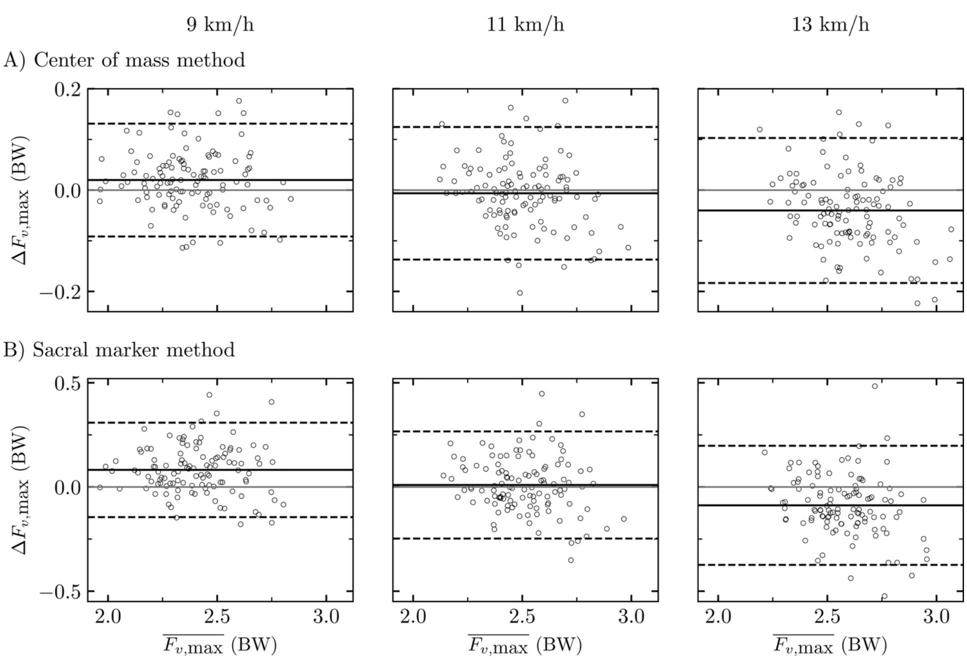

Fig. 3. Comparison of peak vertical ground reaction force [$F_{v,\max}$; in body weight (BW)] obtained using gold standard method and A) center of mass method and B) sacral marker method [differences (Δ) as function of mean values together with systematic bias (black solid line) as well as lower and upper limit of agreements (black dashed lines), i.e., Bland-Altman plots] for three running speeds. COM and sacral marker data were filtered at 5 and 4 Hz, respectively, while vertical force was filtered at 20 Hz. Each dot represents the average over the 10 analyzed strides from one subject.

4. Discussion

According to the first hypothesis, a single cutoff frequency minimized RMSE and was different for each method. Indeed, the most accurate estimations of $F_{v,\max}$ were obtained using a 5 and 4 Hz cutoff frequency for the fourth order Butterworth low-pass filtering of COM and sacral marker accelerations, respectively. Besides, according to the second hypothesis, RMSE close to 0.15 BW were obtained for both COM-M and SACR-M at each tested speed (RMSE $\leq$ 0.17 BW). Conventional statistical approaches demonstrated no systematic bias and no significant difference of $F_{v,\max}$ between GSM, COM-M, and SACR-M at 11 km/h. However, systematic biases and significant differences were obtained at 9 and 13 km/h, though COM-M gave systematic biases three times smaller than SACR-M as well as two times smaller RMSE. Nonetheless, systematic biases at 9 and 13 km/h were small ($\leq$0.09 BW) and accompanied with $\leq$6.5 % RMSE.

COM-M and SACR-M depicted the smallest RMSE for a cutoff frequency of 5 and 4 Hz, respectively (Fig. 1). As the body segments were not considered in the sacral acceleration, this might not attenuate and "smooth" the signal compared to COM acceleration (the whole-body COM trajectory being a weighted sum of all body segments, its overall shape should be smoother than the sacral marker trajectory). This suggests that the vertical peaks in the unfiltered sacral acceleration signal were slightly higher than in COM acceleration (see Fig. S1). Therefore, a smaller cutoff frequency was required to filter the sacral than COM acceleration to decrease the magnitude of the vertical peaks and to make them match with the ones of GSM. Nonetheless, as the sacral marker should be close to COM location [25], the corresponding acceleration signals should be similar, i.e., the noise in the sacral acceleration was not drastically larger than in the COM one, justifying the small difference of 1 Hz in optimal cutoff frequencies.

Different RMSE between speeds were reported at lower than optimal cutoff frequencies while similar RMSE were obtained at larger than optimal cutoff frequencies (Fig. 1). In other words, the effect of speed on

Table 1

Systematic bias, lower limit of agreement (lloa), upper limit of agreement (uloa), and root mean square error [RMSE; both in absolute (body weight; BW) and relative (%) units] between peak vertical ground reaction force ($F_{v,\max}$) obtained using center of mass (COM-M) and gold standard (GSM) method as well as using sacral marker method (SACR-M) and GSM at three running speeds. 95 % confidence intervals are given in square brackets [lower, upper].

	Running Speed (km/h)	Systematic Bias (BW)	Lloa (BW)	Uloa (BW)	RMSE (BW)
COM-M vs GSM	9	0.02 [0.01, 0.03]	−0.09 [−0.11, −0.07]	0.13 [0.11, 0.15]	0.06 (2.6 %)
	11	−0.01 [−0.02, 0.01]	−0.14 [−0.16, −0.12]	0.12 [0.10, 0.15]	0.07 (2.7 %)
	13	−0.04 [−0.05, −0.03]	−0.18 [−0.21, −0.16]	0.10 [0.08, 0.13]	0.08 (3.2 %)
SACR-M vs GSM	9	0.08 [0.06, 0.10]	−0.14 [−0.18, −0.11]	0.31 [0.27, 0.34]	0.14 (6.0 %)
	11	0.01 [−0.01, 0.03]	−0.25 [−0.29, −0.21]	0.27 [0.23, 0.31]	0.13 (5.3 %)
	13	−0.09 [−0.11, −0.06]	−0.37 [−0.42, −0.33]	0.20 [0.15, 0.24]	0.17 (6.5 %)

Note: for systematic bias, positive and negative values indicate the COM-M and SACR-M methods overestimated and underestimated $F_{v,\max}$, respectively. COM and sacral marker data were filtered at 5 and 4 Hz, respectively, while vertical force was filtered at 20 Hz.

Table 2

Peak vertical ground reaction force [$F_{v,\max}$; in body weight (BW)] obtained using gold standard (GSM), center of mass (COM-M), and sacral marker (SACR-M) methods for three running speeds. Significant ($P \leq 0.05$) method of calculation, running speed, and interaction effect, as determined by repeated measures ANOVA, are reported in bold font. *, †, and ‡ depict significant differences between $F_{v,\max}$ obtained using GSM and COM-M, GSM and SACR-M, and COM-M and SACR-M, respectively, at a given running speed and as determined by Holm post hoc tests. Noteworthy, the other pairwise post hoc comparisons were all statistically significant ($P \leq 0.03$) except the pair GSM at 11 km/h and SACR-M at 13 km/h ($P = 0.23$) but not represented by a symbol in the table.

	Running Speed (km/h)	GSM	COM-M	SACR-M
	9	$2.25 \pm 0.28^{*,\dagger}$	$2.27 \pm 0.28^{\ddagger}$	2.33 ± 0.29
$F_{v,\max}$ (BW)	11	2.39 ± 0.30	2.38 ± 0.29	2.40 ± 0.30
	13	$2.50 \pm 0.31^{*,\dagger}$	$2.46 \pm 0.30^{\ddagger}$	2.41 ± 0.30
Method of calculation effect		$P = 0.41$		
Running speed effect		$\boldsymbol{P < 0.001}$		
Interaction effect		$\boldsymbol{P < 0.001}$		

Note: values are presented as mean ± standard deviation. COM and sacral marker data were filtered at 5 and 4 Hz, respectively, while vertical force was filtered at 20 Hz.

RMSE increased as cutoff frequency decreased. This might be explained by the fact that the 2−4 Hz cutoff frequencies were close to the oscillatory behavior of COM or sacral marker. Indeed, 3 Hz is considered as the frequency corresponding to the vertical sinusoidal pelvic motion, reflective of step frequencies [28]. Besides, the higher the speed, the higher the step rate, and thus the even more likely to be close to the oscillatory behavior of the COM or sacral marker, further explaining the higher RMSE reported at 13 km/h than at 11 km/h and 9 km/h at lower than optimal cutoff frequencies.

A previous study evaluating the effect of the cutoff frequency to filter sacral-mounted IMU data to estimate $F_{v,\max}$ reported that the smallest RMSE was obtained using a 10 Hz cutoff [12]. The present study reported optimal cutoff frequencies that were two times smaller (4 and 5 Hz). The discrepancy might be explained by the fact that the authors were directly measuring the sacral acceleration, which might be more prone to high frequency noise [12]. Furthermore, ground reaction force was filtered at 30 Hz whereas a 20 Hz cutoff was used in this study. In addition, the authors recorded treadmill runs from 13.7 to 19.4 km/h, which is faster than the endurance speeds used in the present study. Therefore, as the present study slightly overestimated and underestimated $F_{v,\max}$ at 9 and 13 km/h, respectively, this suggests that a larger cutoff frequency should be used at a faster speed and a smaller one at a slower speed, which goes in the direction of the previous findings [12]. Indeed, increasing/decreasing the cutoff frequency increases/decreases the magnitude of the filtered signal [12]. Moreover, a significant effect of running speed was observed (Table 2). Therefore, a speed-dependent cutoff frequency would probably provide better results. However, future studies should focus on testing several slower and faster running speeds to further decipher the running speed effect. Besides, a more complicated model could be constructed to better estimate $F_{v,\max}$, for instance following recent research [13,33,34], which use artificial intelligence to estimate the vertical ground reaction force. Then, in practice, a systematic addition of the bias corresponding to the given speed could be applied when estimating $F_{v,\max}$.

The differences between GSM and COM-M or SACR-M obtained in this study reported the same level of accuracy than in the study based on a single participant [26] [≤100 N (≤0.15 BW for a 70 kg person) at 7−20 km/h]. Moreover, $F_{v,\max}$ estimated using sacral-mounted inertial sensors reported similar differences [12] [≤20 N (≤0.03 BW for a 70 kg person) at 14−19 km/h] and RMSE [13] (0.15 BW at 13.5–19.5 km/h) with respect to GSM than COM-M and SACR-M used in the present study. In addition, a 6 % error on $F_{v,\max}$ (6−21 km/h) was reported using an inertial sensor placed on the leg along the tibial axis [35] while a 3 % error (10−14 km/h) was achieved using three IMUs (two on lower legs and one on pelvis) and two artificial neural networks [36]. Thus, estimated $F_{v,\max}$ depicted similar error (∼5 %) than previous estimations which used whole-body COM trajectory or inertial sensors. Nonetheless,

Table 3

Cohen's *d* effect size for peak vertical ground reaction force obtained using gold standard method (GSM) and center of mass method (COM-M), GSM and sacral marker method (SACR-M), and COM-M and GSM-M for three running speeds.

	Running Speed (km/h)	GSM vs COM-M	GSM vs SACR-M	COM-M vs SACR-M
	9	−0.10	−0.42	−0.33
d	11	0.03	−0.05	−0.09
	13	0.22	0.49	0.29

Note: COM and sacral marker data were filtered at 5 and 4 Hz, respectively, while vertical force was filtered at 20 Hz.

the present study only tested running speeds ranging between 9 and 13 km/h, thus not permitting to generalize on the accuracy of COM-M and SACR-M at faster running speeds, especially because a significant effect of running speed was observed (Table 2).

No systematic bias and significant difference were reported for both COM-M and SACR-M at 11 km/h (Fig. 3 and Tables 1 and 2). However, systematic but small biases were reported at 9 and 13 km/h (Fig. 3 and Table 1), which were accompanied with significant differences (Table 2). The systematic bias of SACR-M was almost three times larger than the one of COM-M at 9 and 13 km/h while RMSE and effect size were two times larger (Fig. 3, Tables 1 and 3). Besides, a less important linear increase in $F_{v,\max}$ with increasing speed was reported for SACR-M than for GSM and COM-M (Table 2). These results could be explained by the fact that the speed-dependence of the cutoff frequency might be more important for SACR-M than COM-M, which is depicted by the larger range of RMSE over the three running speeds at a given cutoff frequency for SACR-M than COM-M (Fig. 1). Therefore, SACR-M might require a more pronounced variation of the cutoff frequency with running speed than COM-M, i.e., the cutoff frequency for SACR-M might need to vary (even if <1 Hz) when speed changes by 2 km/h while the one of COM-M might not. This might allow to obtain a similar linear increase of $F_{v,\max}$ with increasing speed for SACR-M than for GSM and COM-M. Nonetheless, further studies should be conducted to validate this assumption.

No significant difference was reported between COM-M and SACR-M at 11 km/h but were at 9 and 13 km/h (Table 2), which follows the differences between GSM and both COM-M and SACR-M. However, SACR-M depicted larger deviations around the mean than COM-M, as reported by the larger lower and upper limit of agreements (Fig. 3) and 95 % CI (Table 1). These larger deviations could be explained by the fact that the whole-body COM trajectory is a weighted sum of all body segments while the sacral marker trajectory is obviously not. Indeed, the overall shape of the whole-body COM trajectory being smoother than the sacral marker one (see Fig. S1), the difference between participants tends to be smaller for the COM trajectory, which is then reflected in the acceleration signals obtained by double differentiation. These findings showed that COM-M is more consistent amongst participants than SACR-M and might be a preferred choice but is not reflected by the statistical analysis. Therefore, we suggest researchers with access to a motion capture system but not to a force plate to use COM-M or SACR-M with data filtered at 5 and 4 Hz, respectively, to estimate $F_{v,\max}$. Furthermore, similar methods but employing a sacral-mounted IMU might be used to estimate $F_{v,\max}$ overground, as long as an optimal cutoff frequency has been determined [12].

As a limitation to the present study, a single cutoff frequency was used to filter the vertical ground reaction force, i.e., 20 Hz. Though this choice of cutoff frequency is quite widespread [37,38], other cutoff frequencies (e.g., 30 or 80 Hz) are also used in the literature [12,13,39]. In this case, the optimal cutoff frequencies reported in this study and of 5 and 4 Hz for COM-M and SACR-M, respectively, might not be valid anymore because $F_{v,\max}$ calculated using GSM might be different. Hence, further studies investigating the effect of the cutoff frequency of the gold standard signal should be conducted.

5. Conclusion

To conclude, this study proposed to estimate $F_{v,\max}$ by reconstructing the vertical ground reaction force from either the whole-body COM or sacral marker accelerations (Eq. 1), themselves obtained by double differentiations of their respective trajectories and further low-pass filtered using a fourth-order Butterworth filter. The most accurate estimations of $F_{v,\max}$ were obtained using a 5 and 4 Hz cutoff frequency for the filtering of COM and sacral marker accelerations, respectively. The comparison between GSM and COM-M or SACR-M, using data filtered at 5 and 4 Hz, respectively, depicted RMSE $\leq$0.17 BW ($\leq$6.5 %), together with no systematic bias at 11 km/h and systematic but small biases at 9 and 13 km/h ($\leq$0.09 BW). No significant difference was reported between each pair of methods at 11 km/h but were at 9 and 13 km/h, The findings of this study support the use of either COM-M or SACR-M using data filtered at 5 and 4 Hz, respectively, to estimate $F_{v,\max}$ during level treadmill runs at endurance speeds.

Author contributions

Conceptualization, A.P., T.L., C.G., and D.M.; methodology, A.P., T. L., C.G., and D.M.; investigation, A.P., T.L., and B.B.; formal analysis, A. P. and B.B.; writing—original draft preparation, A.P.; writing—review and editing, A.P., T.L., B.B., C.G., and D.M.; supervision, A.P., T.L., C.G., and D.M.

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Availability of data and material

The datasets supporting this article are available on request to the corresponding author.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2021.07.013.

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