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Short communication

Foot centre of pressure and ground reaction force during quadriceps resistance exercises; a comparison between force plates and a pressure insole system

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ABSTRACT

The study compared the centre of pressure measurements (COP) and vertical ground reaction forces (vGRF) from a pressure insole system to that from force plates (FP) during two flywheel quadriceps resistance exercises: leg press and squat. The comparison was performed using a motion capture system and simultaneous measurements of COP and vGRF from FP and insoles. At lower insole-vGRF (<250 N/insole) COP accuracy deteriorated and those data were excluded from further analysis. The insoles systematically displaced the COP slightly posteriorly and medially compared to the FP measurements. Pearson's coefficient of correlation (r) between insole- and FP-COP showed good agreement in both the anteroposterior (squat: $r = 0.96$, leg press: $r = 0.97$) and mediolateral direction (squat: $r = 0.84$, leg press: $r = 0.90$), whereas the root-mean-square errors (RMSE) were lower in the mediolateral (squat: 3.9 mm, leg press: 4.5 mm) than the anteroposterior (squat and leg press: 11.8 mm) direction. Vertical GRF was slightly overestimated by the insoles in leg press and RMSE were greater in leg press (8% of peak force) than in squat (6%). Overall, results were within the range of previous studies performed on gait. The strong agreement between insole and FP measurements indicates that insoles may replace FPs in field applications and biomechanical computations during resistance exercise, provided that the applied force is sufficient.

1. Introduction

Biomechanical analysis of human movement generally requires knowledge about ground reaction forces (GRF) and centre of pressure (COP) (Hamill et al., 2015). The conventional way to obtain this information is to measure these variables using force plates (FPs) (Zeni et al., 2008). However, since FPs are immobile and cumbersome to use (Skals et al., 2017), alternative methods to obtain GRF and COP are often desired in field applications.

Several studies have developed and evaluated methods for predicting GRF (Fluit et al., 2014; Jung et al., 2016; Karatsidis et al., 2017; Ren et al., 2008; Skals et al., 2017). A few studies have used insole pressure measurement systems (insoles) to measure the vertical component of the GRF (vGRF) and its COP (Fong et al., 2008; Forner Cordero et al., 2004). Insoles have been examined regarding their validity and reliability to assess regional foot pressure or vGRF during locomotion (Koch et al., 2016; Price et al., 2016; Ramanathan et al., 2010; Seiberl et al., 2018; Stöggl and Martiner, 2017). Their capacity to measure vGRF or COP has mostly been studied during gait (Chesnin et al., 2000; Chevalier et al., 2010; Chumanov et al., 2010; Debbi et al., 2012; Dyer and Bamberg, 2011). The results have indicated that even though COP derived from insoles deviate from those obtained by FPs, they can be useful to approximate COP location and gait parameters when FPs are impractical to use, provided that the spatial resolution and the sampling rate are sufficient (Chevalier et al., 2010; Dyer and Bamberg, 2011). It is also recommended, due to the varying designs of insoles and their data processing, that each system has its accuracy tested independently (Chesnin et al., 2000).

In general, information is scarce regarding how well insole systems perform during activities other than gait, and in particular, their measurement performance is unknown in activities involving resistance exercise, as is typically performed at slow speed sustaining a substantial load through both feet. The aims of the present study were to compare the COP and vGRF measurements from a pressure insole system with those from a FP system during flywheel quadriceps resistance exercise, performed with two

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Nomenclature

AP	anteroposterior	vGRF	vertical ground reaction force
COP	centre of pressure	ML	mediolateral
FP	force plate	r	Pearson's coefficient of correlation
FWED	flywheel exercise device	RMSE	root mean square error
GRF	ground reaction force	Δ	deviation (difference between FP- and insole values)

different alignments of the foot-contact plane and the body posture; i.e. during leg press and squat.

2. Methods

Five women and six men, all healthy, gave their informed consent to participate. The experimental protocol and procedures were approved by the Regional Human Ethics Committee in Stockholm. The participants age, height and mass were (mean ± SD): 24 ± 2 yrs, 1.73 ± 0.07 m, 69.5 ± 11.3 kg.

COP and vGRF were measured in two ways: using insoles, (Pedar-X®, Novel GmbH, Munich, Germany, sampling rate 100 Hz) and FPs (Bertec corporation, Columbus, US, sampling rate 2000 Hz). The FPs were mounted on the foot support of a custom-made, convertible flywheel exercise device (FWED) (Berg and Tesch, 1994). The insoles, each containing 99 pressure cells, were tried out for best fit and placed within a pair of indoor football shoes (Kipsta Agility 100Hg). Before commencing data collection, the insoles were reset in an unloaded state, with shoes on. A motion-capture system with eight cameras (ProReflex MCU 240, Qualisys AB, Gothenburg, Sweden, sampling rate 100 Hz) was used to record the positions of 6 retro-reflective markers, representing the bilateral locations of the first and fifth metatarsal head and the heel. Using the FWED, each participant performed weighted squat and leg-press trials at loads corresponding to 80–100% of isometric leg-press maximum. The squat was performed standing on the FWED and the leg press sitting on a low-friction horizontally sliding seat, with the feet positioned on the FWED at a 60° angle relative to the floor (Fig. 1). In both squat and leg press, the participant was connected to the FWED via a strap attached to a harness.

2.1. Centre of pressure transformation

FP-COP was measured in a global coordinate system defined by the motion-capture system, while the insole-COP was measured in its local insole coordinate system. To compare the two measurements a transformation was done, using the locational information of the foot markers, being identifiable in both coordinate systems. In the global system, the cameras continuously measured the marker positions, whereas in the insole system, their positions were estimated once for each insole size. This was done by manually applying a pressure to the insole at the closest point to each marker, followed by correcting the output value for shoe thickness and marker radius.

A rigid body transformation was assumed, and the rotation matrix, R_{3x3}, and translation vector, $\mathbf{t}_{3x1}$, were calculated by optimally aligning the two marker sets in a least-squares sense, as described in Eq. (1),

$$(R,\mathbf{t}) = \underset{R,\mathbf{t}}{\operatorname{argmin}} \sum_{i=1}^{n} \|(R\mathbf{p}_i + \mathbf{t}) - \mathbf{q}_i\|^2 \quad (1)$$

where n represents number of markers, and $\mathbf{p}_{3x1}$ and $\mathbf{q}_{3x1}$ represent the marker positions in the global and insole coordinate systems, respectively (cf. Arun et al., 1987).

2.2. Analyses and force-level criteria for COP measurements

Nineteen squat and 19 leg-press trials were included. Three consecutive repetitions from each trial were selected for data analysis. Symmetrical results were found; thus, data are only presented for the left foot. Analyses were performed using Matlab R2018b (The MathWorks Inc., Natick, US) and Excel 2016 (Microsoft Corporation, Redmond, US).

To evaluate the insole measurements, data derived from the FP were regarded as reference values. COP deviation was evaluated in the anteroposterior (AP) and mediolateral (ML) directions and for vGRF conformity, the force measured by the insole was compared to the vertical component of the FP-GRF.

Load dependency was found for the deviation of insole-COP from FP-COP. Insole-COP values were substantially more imprecise at low loads, with deviations of up to 100 mm (Figs. 2 and 3C). To exclude ambiguous data, AP-COP deviation was analysed in relation to 50-N insole-force decrements (Fig. 2) using a 3-period centred moving average procedure; any average deviating by ≥15% from the previous value was excluded. Thus, COP-data included in further analyses were those at insole-vGRF exceeding 250 N.

The deviation (Δ) between insole and FP measurements were calculated at all time steps and averaged for each trial. Pearson's correlation coefficient (r) and the root-mean-square error (RMSE) were computed for each trial. Differences between insole and FP measurements, and between leg-press and squat values were evaluated by two-tailed T-tests, with p-values < 0.05 being regarded statistically significant. Values are means ± SD, unless otherwise stated.

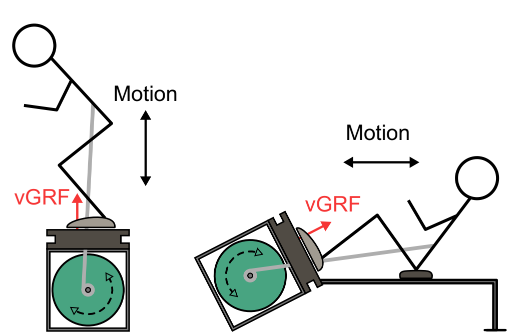

Fig. 1. Schematic illustration of squat (left) and leg press (right) performed on a flywheel exercise device (FWED). The participant is connected to the FWED via a strap attached to a harness. vGRF indicates the vertical component of the ground reaction force. Direction of motion is virtually perpendicular to the foot-plane in squat, whereas in leg press the motion is directed at an angle generating a greater portion shear force in the ground reaction.

3. Results

Insole-COP was displaced posteriorly, by up to 10 mm in relation to FP-COP ($p < 0.001$; Table 1, Fig. 3A). A medial displacement

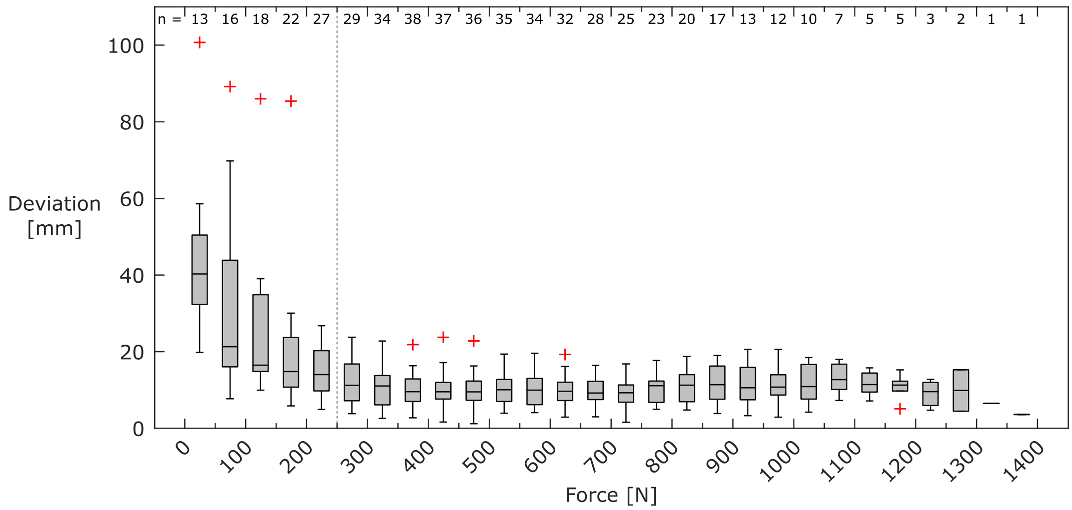

Fig. 2. Tukey's box plot showing anteroposterior centre of pressure (COP) deviation in relation to force load on one insole for all trials. Data points within 50-N force intervals were averaged for each trial. Bottom and top edges of the box show data between 25th and 75th percentile, the central mark indicates the median, whiskers extend to data within the 1.5th interquartile range and outliers are indicated by a '+'. The dashed line illustrates the force, below which the centred moving averages of consecutive COP deviations differed by ≥15%, and hence were excluded from further analysis. Number of data points (n) included in each box is indicated at the top of the graph window.

was found when studying all trials (−1.5 ± 4.5 mm, $p = 0.04$) or squat trials (−2.1 ± 2.8 mm, $p = 0.005$), but not leg-press trials.

RMSE for COP values were greater ($p < 0.001$) in the AP (11.8 mm) than the ML direction (squat: 3.9 mm, leg press: 4.5 mm). Correlations in COP measurements ranged from 0.84 for squat trials in the ML direction to 0.97 for leg-press trials in the AP direction (Table 1).

Overall, vGRF showed excellent correlation ($r = 0.98$), but the magnitude was exaggerated by the insoles in leg-press trials ($p = 0.007$; Table 1, Fig. 3B). RMSE in vGRF measurements were 44.9 N and 65.4 N in squat and leg press, respectively, corresponding to 5.6% and 8.3% of the peak force. Significant differences between squat and leg press were only found in vGRF deviation ($p = 0.01$) and RMSE ($p = 0.02$).

4. Discussion

Overall, good agreements in COP and vGRF assessments were demonstrated, when comparing insole and FP recordings during the loaded phase of lower-limb resistance exercise. Notwithstanding, at lower insole-vGRF COP accuracy gradually deteriorated, and with an inclined footplate causing shear stress on insoles, a slight overestimation of vGRF occurred.

During squats, the insoles remain loaded by the body weight throughout the exercise repetition. By contrast, during leg press, gravity does not act towards the feet and the loads may drop to almost zero at the end of the push-off phase, in a similar manner as during the heel-contact or toe-off phases of running or walking. These low-loaded phases presented difficulties when using insoles to assess COP during a complete movement cycle, COP accuracy deteriorating at insole-vGRF < 250 N (Figs. 2, 3C). Presumably, because at low total load, a substantial share of the load is distributed to individual insole sensors located at the edge of the weight-bearing area, and not loaded to their pressure-measurement threshold (15 kPa). At high total loads, by contrast, the influence on COP from any sub-threshold loaded peripheral sensors will be minute.

Even after excluding COP-data at vGRF < 250 N, insole-COP exhibited a slight posteromedial dislocation, to which several factors may have contributed. Firstly, the insoles might have moved slightly within the shoes, despite that they were carefully tried out for best shoe fit. Secondly, there is an inherent difference between the two systems, measuring COPs at different surfaces, one between the foot and the shoe and the other between the shoe and FP. This may skew any comparison between the two systems, since the shoe could redistribute some of the load applied by the foot to a different area in situations where the applied force is not perpendicular to the surface (cf. Chevalier et al., 2010). Finally, the marker positions were estimated in the insole coordinate system and a rigid transformation was used, not considering any deformation of the foot, insole or shoe (Kim and Nussbaum, 2014). Regardless of which of these factors contributed to the posteromedial COP shift, their impact on the COP values was small and of little practical consequence.

Correlations between insole-COP and FP-COP ranged from 0.84 to 0.97, with higher correlations in the AP than ML direction. Also, the COP RMSE were consistently lower in the ML than AP direction. This could probably be explained by the longer COP-trajectory in the sagittal than transversal foot plane (Fig. 3A; cf. Debbi et al., 2012). When comparing insoles and FPs during gait, correlations and RMSE have been reported to range from 0.35 to 0.87 and 4 to 15 mm, respectively, in the ML direction, and from 0.90 to 0.99 and 9 to 57 mm in the AP direction (Chesnin et al., 2000; Chumanov et al., 2010; Debbi et al., 2012; Dyer and Bamberg, 2011); thus, present data are within the range of previous studies. Interestingly, COP trajectories assessed by insoles during gait have demonstrated extensive deviations at foot contact and toe-off phases (Chumanov et al., 2010; Forner Cordero et al., 2004). For example, Chumanov et al. (2010) showed RMSE up to 57 mm, 12 mm and 44 mm in the first, middle and last stance phase, respectively. Presumably, the momentarily low vGRF in the first and last phases contributed to their high RMSE values. It thus appears that COP registration with insoles should be used with caution in activities with low vGRF, e.g. resistance exercise where body weight is alleviated.

Present force outputs showed correlations between insole and FP similar to, or better than, those reported in comparable studies (Fong et al., 2008; Forner Cordero et al., 2004; Seiberl et al., 2018). RMSE were 6% and 8% of the peak force for squat and leg press, respectively. RMSE and relative peak force values, corresponded well with those reported in studies comparing insole to FP data during walking or running (Chumanov et al., 2010; Fong et al., 2008; Forner Cordero et al., 2004).

Insole-vGRF were exaggerated in leg press but accurate in squat. The discrepancy may be attributed to the different orienta-

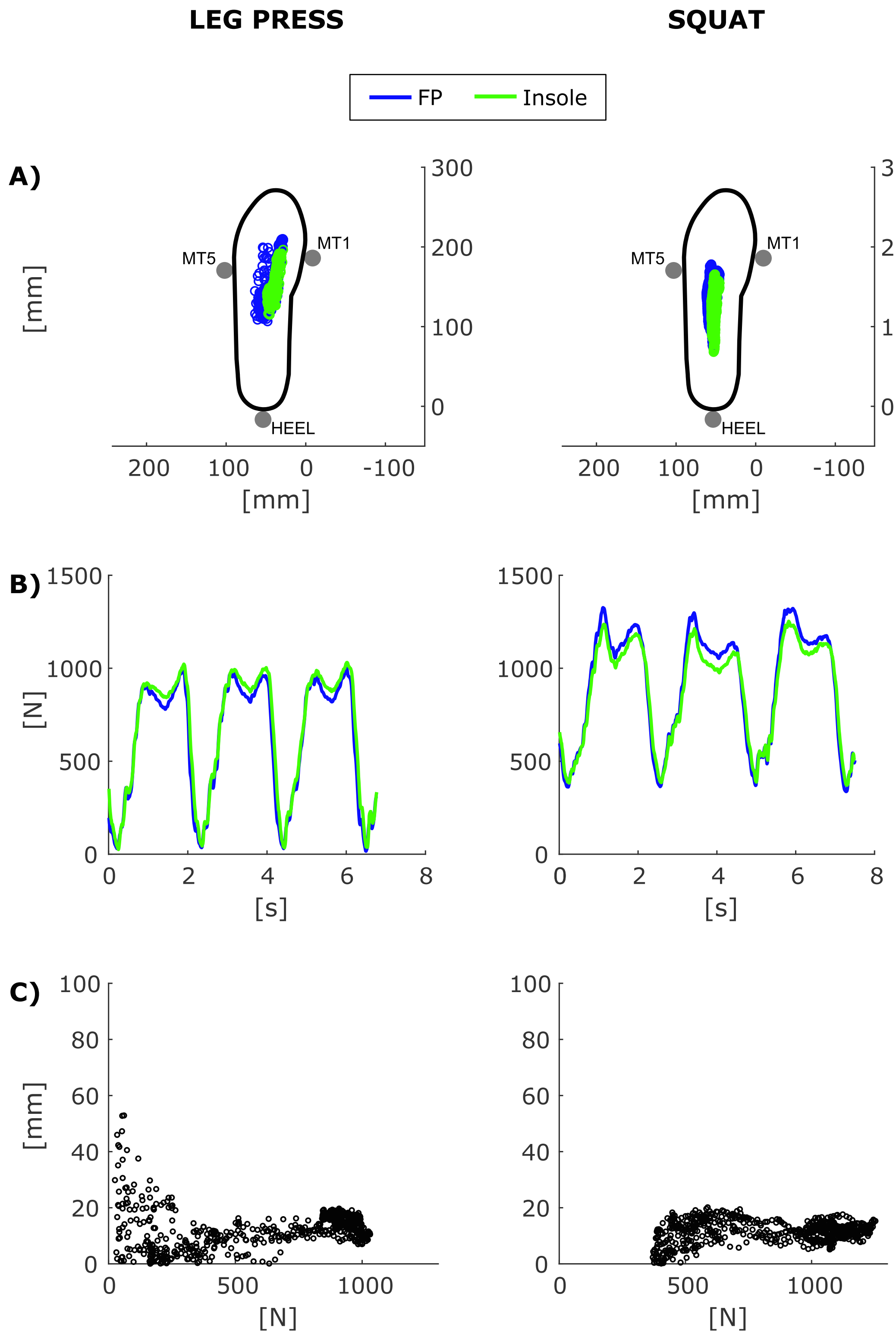

Fig. 3. Data from one typical subject performing three consecutive repetitions for leg press (left) and squat (right) at 80% of isometric maximum. (A) Centre of pressure (COP) distribution of force plate (FP; blue) and insole (green) measurements for the left foot in the insole coordinate system. Note that this subject exhibited a slight medial displacement of the insole COP. Grey dots represent the three retro-reflective motion capture markers. (B) Vertical ground reaction force (vGRF) from FP (blue) and insole (green) measurements. Note that during squat-movement cycles, vGRF never falls below 400 N, whereas during leg press vGRF is near 0 N during the knee-extension phases. (C) Anteroposterior COP deviation in relation to the insole measured vGRF. Note the greater COP deviation between FP and insole measurements at low insole vGRF, occurring solely during leg-press exercise.

tion of the foot plane in relation to the direction of applied force. In squat, the force was applied virtually perpendicular to the foot plane whereas in leg press it was applied at an angle to the foot plane (Fig. 1). Consequently, the portion of the applied force consisting of anterior shear was larger in leg press than squat. As insoles calculate force from pressure applied to the surface, the

Table 1
Comparison of data measured by insoles and force plates (FP). Centre of pressure (COP) data are presented for mediolateral (ML) and anteroposterior (AP) directions. vGRF data are vertical ground reaction forces. Deviation (Δ), root-mean-square error (RMSE) and Pearson's correlation (r) between the two measurement methods are presented for all trials (All), and leg press and squat trials separately. Values are mean (SD or % of peak force).

Exercises	COP[§]						vGRF		
	Δ_{ML} [mm]	$RMSE_{ML}$ [mm]	r_{ML}	Δ_{AP} [mm]	$RMSE_{AP}$ [mm]	r_{AP}	Δ [N]	RMSE [N]	r
All	−1.5 (4.5)[*]	4.2	0.87	−9.6 (4.9)[***]	11.8	0.96	13.7 (49.1)	55.2 (7.0%)	0.98
Leg press	−0.9 (5.5)	4.5	0.90	−9.1 (5.3)[***]	11.8	0.97	36.1 (51.6)[**,‡]	65.4[‡] (8.3%)	0.99
Squat	−2.1 (2.8)[**]	3.9	0.84	−10.0 (4.4)[***]	11.8	0.96	−8.8 (34.1)[‡]	44.9[‡] (5.6%)	0.98

Note. Negative values indicate a medial or posterior deviation of insole-COP and a lower insole-vGRF compared to FP-values.
§ COP values are analyzed for those parts where insole vGRF were above 250 N.
* Significant difference between insole and FP measurements ($p < 0.05$).
** Significant difference between insole and FP measurements ($p < 0.01$).
*** Significant difference between insole and FP measurements ($p < 0.001$).
‡ Significant difference between leg press and squat ($p \leq 0.02$).

device cannot discern the direction of force applied. Thus, during leg press, anterior shear force presumably contributes to insole vGRF, whereas FPs detect shear forces separately and do not include them in the vGRF signal.

In conclusion, considering that peak loads during resistance exercise typically reach 2–4 times body weight (cf. Berg and Tesch, 1994), insoles may successfully replace FPs for COP and vGRF measurements in resistance-exercise field applications and biomechanical computations.

Author contribution

HB and MJ initiated and designed the study. MJ, LN and TM performed the experiments. MJ and TM analysed the data and drafted the manuscript. All authors interpreted the data and participated in the preparation of the final manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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