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Short communication

Estimating the complete ground reaction forces with pressure insoles in walking

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Abstract

This study presented a method to estimate the complete ground reaction forces from pressure insoles in walking. Five male subjects performed 10 walking trials in a laboratory. The complete ground reaction forces were collected during a right foot stride by a force plate at 1000 Hz. Simultaneous plantar pressure data were collected at 100 Hz by a pressure insole system with 99 sensors covering the whole plantar area. Stepwise linear regressions were performed to individually reconstruct the complete ground reaction forces in three directions from the 99 individual pressure data until redundancy among the predictors occurred. An additional linear regression was performed to reconstruct the vertical ground reaction force by the sum of the value of the 99 pressure sensors. Five other subjects performed the same walking test for validation. Estimated ground reaction forces in three directions were calculated with the developed regression models, and were compared with the real data recorded from force plate. Accuracy was represented by the correlation coefficient and the root mean square error. Results showed very good correlation in anterior–posterior (0.928) and vertical (0.989) directions, and reasonable correlation in medial–lateral direction (0.719). The root mean square error was about 12%, 5% and 28% of the peak recorded value. Future studies should aim to generalize the methods or to establish specific methods to other subjects, patients, motions, footwear and floor conditions. The method gives an extra option to study an estimation of the complete ground reaction forces in any environment without the constraints from the number and location of force plates.

Keywords: Kinetics; Plantar pressure; Gait; Biomechanics

1. Introduction

Ground reaction forces are often investigated in gait biomechanics studies (Kitaoka et al., 2006). However, the measurement is often restricted by the number and the location of force plates. In attempt to measure vertical and shear ground reaction forces without such restriction, different devices were developed, such as a thin layer of strain gauge transducer (Davis et al., 1998) or piezoelectric copolymer film (Razian and Pepper, 2003), and instrumented shoe with two sensors mounted beneath the forefoot and rearfoot (Liedtke et al., 2007; Schepers et al., 2007). However, these devices were limited to its specific purpose and thus were not readily available for other researchers. For example, although the instrumented shoe with two external mounted sensors beneath the forefoot and rearfoot (Liedtke et al., 2007; Schepers et al., 2007) could measure complete shear and vertical ground reaction force, the external device lifts the shoe sole and separates it from the ground by the two mounting frames. This changes the original interface between shoe

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sole and the ground to an interface between the mounting frames and the ground, and could probably alter the friction between the contact interface. Moreover, it may increase the height of the effective sole and also the weight of the sole. For the shoe with an instrumented insole with strain gauge transducer or piezoelectric copolymer film, the high cost of the sensor resulted in the use of a limited number of sensors, and thus an inadequate coverage of the whole plantar region. For example, the complete ground reaction forces could only be measured in the forefoot region with 16 sensors in the device of Davis et al. (1998), and at only four selected regions (heel, toe, 1st and 5th metatarsal head) in the device of Razian and Pepper (2003).

Recently, Forner Cordero et al. (2004) developed a method to calculate the complete ground reaction forces during gait by incorporating pressure insole data and kinematics data in a validated calculation algorithm. The kinematics data provided information for the transformation between the insole reference frame and the global reference frame, which facilitated the subsequent calibration of the vertical ground reaction force and the computation of the complete ground reaction force. Although the results were excellent, the method relied on kinematics data from a motion capture system and thus was still not readily applicable in outdoor environment, as it often requires substantial effort in calibrating outdoor environment for kinematics measurement. Moreover, the vision-based motion measurement systems often have a limited measurement volume as dictated by the vision field of the cameras. Another previous study suggested that the plantar pressure distribution was related to the shear ground reaction force (Savelberg and de Lange, 1999). The result suggested a mechanical relation between plantar pressure and shear ground reaction force, which led to the current attempt to develop a method and test the feasibility to estimate the complete ground reaction forces with only pressure insole data during walking in a small group of subjects. As the new method is free from the restrictions of force plate and motion capture system, it is suitable for rapid on-field measurement in all settings, provided that the subsequent future studies to generalize the method on other subject groups are successful.

2. Method

2.1. Calibration test

Five right-legged male subjects (age = 23.0 ± 3.0 yr, height = 1.72 ± 0.03 m, body mass = 65.1 ± 9.7 kg, foot length = 255–260 mm) wore a pair of cloth sport shoes (Fong et al., 2007) and performed 10 trials of walking at their natural cadence on a 10-m walking path in a gait laboratory. The university ethics committee approved the study. In each trial, the subject stepped on a force plate (Advanced Mechanical Technology Inc., USA) located at the middle of the walking path with their right foot. The complete ground reaction forces for the right foot were sampled by the force plate at 1000 Hz. A pair of pressure insoles (Novel Pedar model W, Germany) was inserted in the shoes for the simultaneous measurement of plantar pressure at 100 Hz. There were 99 sensors in each insole, covering the whole plantar area, and recording pressure data with a resolution of 2.50 kPa.

The force plate data and the plantar pressure data for the right foot were trimmed for one complete stride, from the moment of take off before the foot strike on the force plate, until the next take off from the force plate. The first moment of take off before the foot strike on the force plate was identified by the null plantar pressure value as recorded by the pressure insoles. The second moment of take off from the force plate was identified when the vertical ground reaction force as recorded by the force plate drop beneath 10 N. The force plate data were re-sampled to have data point in every 0.01 s to match the sampling frequency of the pressure data. Data from all trials and all subjects were pooled together for stepwise linear regression analysis to reconstruct the value of the ground reaction force in three directions (anterior–posterior, F_{x_fp}; medial–lateral, F_{y_fp}; vertical, F_{z_fp} (N)) by the value of the 99 pressure sensors ($P_1, P_2, \ldots, P_{99}$ (kPa)). In each stepwise regression analysis, predictors were added to the regression models until the inclusion of the next predictor showed redundancy or multicollinearity, as indicated by a tolerance value of less than 0.20 and a variance-inflation factor value of more than 4. An additional linear regression analysis was conducted to reconstruct the vertical ground reaction force by the sum of the value of the 99 pressure sensors (P_{Sum} (kPa)).

2.2. Validation test

Another group of five right-legged male subjects (age = 23.8 ± 3.3 yr, height = 1.74 ± 0.03 m, body mass = 65.4 ± 7.3 kg, foot length = 255–260 mm) participated in the validation test. Independent *t*-tests showed that the two groups of subjects did not differ in age, height and body mass. The subjects performed the walking test with the same procedure with the calibration test. Beside the complete ground reaction forces recorded by the force plate, the estimated ground reaction forces were also calculated by inputting the pressure value of the selected sensor locations to the regression models developed in the calibration test. Correlation coefficient (R) and the root mean square error (RMS error) were computed between the data measured with force plates and estimated from the regression models, for the comparison of accuracy with the method of Forner Cordero et al. (2004).

3. Results

Table 1 shows the results of regression analysis, which included the equations to estimate the value of the complete ground reaction forces recorded from the force plate, and the amount of explained variance (Adjusted R^2) of the regression models. Fig. 1 shows the locations of the sensors included in each regression model employing individual pressure sensor value as predictors. Four, six and four sensors among the total 99 sensors were required for the estimation of the ground reaction force for anterior–posterior, medial–lateral and vertical directions respectively, as shown in Fig. 1. The P_{Sum} was also found to be relevant in reconstructing the vertical ground reaction force.

The accuracy of the estimation was also shown in Table 1, as indicated by the correlation and the RMS error between the real and estimated data. Corresponding results from the study of Forner Cordero et al. (2004) are also included for comparison. Fig. 2 shows the pattern and the absolute error of the real and estimated data of a complete stride trial with an average accuracy among the 50 trials in the validation test. The accuracy of the results was

Table 1
Results of regression analysis and the comparison of accuracy with the study of Forner Cordero et al.

Force direction	Regression models	Adjusted	Accuracy		Study of Forner Cordero et al.	
		R^2	R	RMS error (N)	R	RMS error (N)
Anterior–posterior (F_{x_fp})	F_{x_est} (N) $= 1.364-32.045\times(P_{13})+4.452\times(P_{90})+4.847\times(P_{97})-2.796\times P_{60}$	0.904	0.928	27.41	0.977–0.979	7.53–9.15
Medial–lateral (F_{y_fp})	F_{y_est} (N) $= 2.622-3.158\times(P_{60})-8.734\times(P_{33})-1.508\times(P_{84})-1.654\times(P_{22})+2.261\times(P_{1})-2.310\times P_{19})$	0.764	0.719	11.71	0.778–0.818	7.30–7.51
Vertical (F_{z_fp})	F_{z_est} (N) $= -18.938+8.001\times(P_{74})+31.446\times(P_{18})+30.836\times(P_{71})+15.150\times(P_{1})$	0.975	0.989	45.79	0.995–0.997	27.84–30.13
	$F_{z\_est\_sum}$ (N) $= -31.132+1.696\times(P_{Sum})$	0.985	0.992	38.43	0.995–0.997	27.84–30.13

Unit: force in N, pressure in kPa. P_X is the value of pressure of the sensor number *X*. P_{Sum} is the value of the sum of the pressure values of the 99 sensors.

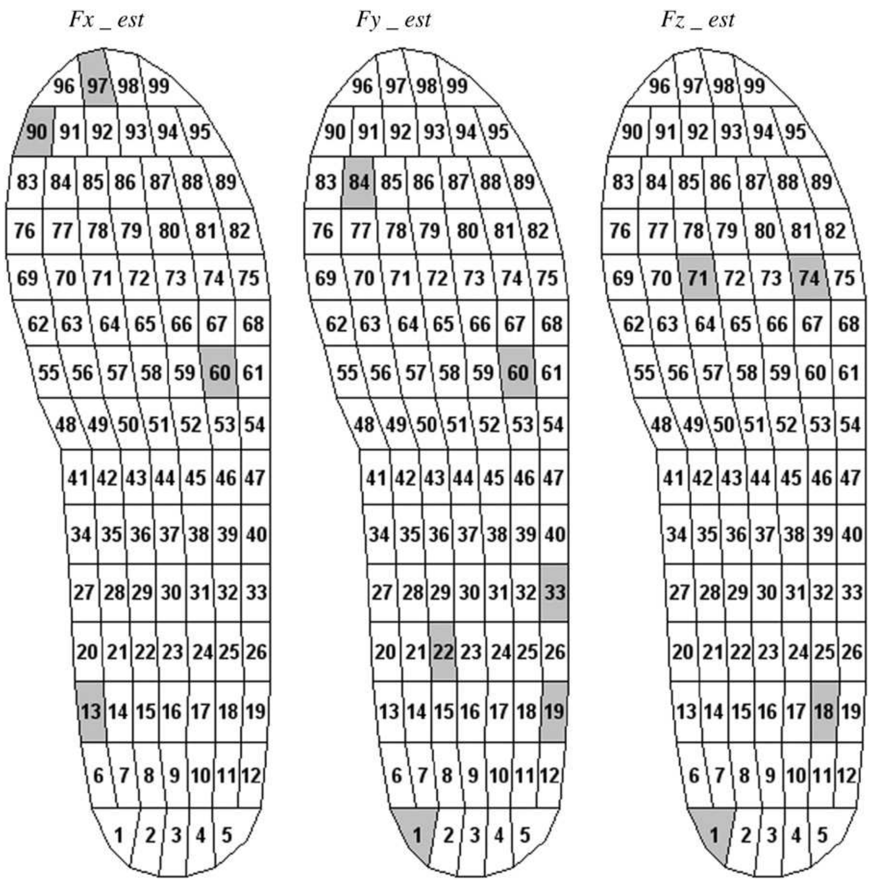

Fig. 1. Location of the sensors (in right foot) required in the three regression models (in grey).

very good in the estimation of ground reaction force in anterior–posterior and vertical directions, as indicated by a very high correlation between the real and estimated data (0.928 and 0.989). The RMS error was 27.41 and 45.79 N, respectively, which was only about 12% and 5% of their peak values. The estimation in medial–lateral direction was fair, with a correlation value of 0.719 between the real and estimated data. The RMS error was 11.71 N, which was as much as 28% of the peak value. In general, the pattern and accuracy of the results of this study were similar but slightly inferior to that from the study of Forner Cordero et al. (2004), as indicated by lower correlations, greater RMS errors and same deficiency in estimating the ground reaction force in medial–lateral direction.

The pattern of the estimated data was similar to that of real data, as shown in a selected trial with average accuracy in Fig. 2. The solid line shows the pattern of the real ground reaction force data as measured by the force plate (F_{x_fp}, F_{y_fp}, F_{z_fp}), and the dotted line showed the estimated data calculated from the regression models

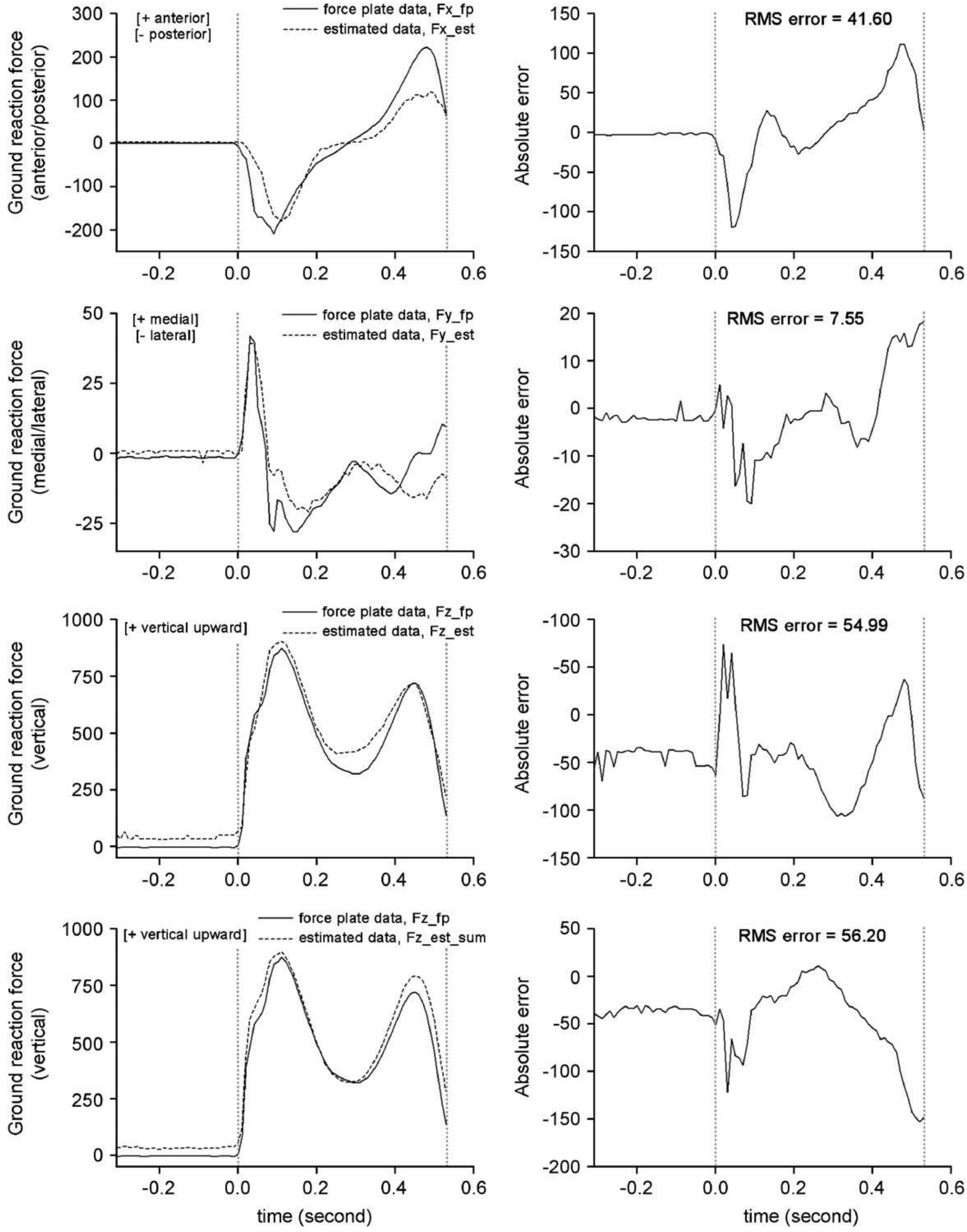

Fig. 2. Pattern and the absolute error of real and estimated complete ground reaction force data in a selected trial of a complete stride, from the previous take off (time = −0.31 s), foot strike (time = 0.00 s) to the next take off (time = 0.53 s), as shown by the dotted lines.

shown in Table 1 (F_{x_est}, F_{y_est}, F_{z_est}, $F_{z\_est\_sum}$). At the time right after the foot strike, the estimation of the peaks was found to be very accurate. The estimated values were about 95–105% of the real data in all three directions. However, the plots of absolute error suggested that the largest error occur right after foot strike and just before take off—this implied that the estimation was even more accurate during the mid-stance period. However, at the period just before take off, relatively larger errors were found in both anterior–posterior and medial–lateral components.

4. Discussion

In the estimation of the vertical force, four critical sensor locations (P_1, P_{18}, P_{71}, P_{74}) or the P_{Sum} could both work well with comparable accuracy. The four locations spread around the plantar region, with two at the metatarsal region and two at the rearfoot region. In the estimation of anterior–posterior shear force, the mechanical relation between plantar pressure and shear ground reaction force was somewhat reflected by the position of the essential pressure sensors for the estimation. The locations P_{13} and P_{60} contributed negatively to the estimated value—when they were on, especially during the heel-strike period and the weight-acceptance period by midfoot, the ground reaction force was in a rather backward direction. The locations P_{90} and P_{97} around the hallux region contributed positively. They were on, especially at the propulsion and take off period, when the hallux was almost the only contact region of the foot and the ground. The corresponding ground reaction force was in the anterior direction for propulsion. This also reflected the characteristics of heel–toe walking, which lead to this unique mechanical relation between plantar pressure and shear ground reaction force in anterior–posterior direction.

This study presented a feasible method to estimate complete ground reaction forces with pressure insole data during walking, however, the current findings are limited to a small homogenous group of male young subjects only. Future studies should aim to generalize the methods, or to establish specific methods to other subjects, patients, motions, footwear and floor conditions, etc. Although the method presented in the current study is slightly inferior to that presented by Forner Cordero et al. (2004), it does not require a motion capture system for the calculation of complete ground reaction force. Therefore, if the level of accuracy is adequate, or if the inferior accuracy could be tolerated, the current method is readily available for measurement in any environment out of the laboratory. Considering the good and reasonable accuracy and the possible rapid application in any environment, the method presented in this study should give an extra option to study complete ground reaction forces with less constraint from the number and location of force plates. Before the future studies to generalize the methods to other conditions, we suggest performing calibration and measurement on the same group of subject with the same type of shoes. The method presented could be implemented to the original pressure insole system for immediately estimation of the complete ground reaction forces during data collection, and could be useful for real-time analysis for sport biomechanics tests which requires immediate display of data and reports.

5. Conclusion

This study presented a feasible method to estimate complete ground reaction forces with pressure insole data during walking, which eliminates the constraint introduced by number and location of force plates in biomechanics studies. The results were very good in estimating anterior–posterior and vertical ground reaction force, and with reasonable accuracy in estimating that in medial–lateral direction. The method can serve as an extra option in measuring complete ground reaction forces in any environment out of the laboratory without using force plates.

Conflict of interest

None declared.

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