ELSEVIER

Journal of Biomechanics 37 (2004) 1427–1432

JOURNAL OF BIOMECHANICS

www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

Use of pressure insoles to calculate the complete ground reaction forces

A. Forner Cordero[a,b,*], H.J.F.M. Koopman[a], F.C.T. van der Helm[a]

[a] *Institute for Biomedical Technology (BMTI), Biomedische Werktuigbouwkunde, CTW Gebouw, Universiteit Twente, P.B. 217, AE Enschede NL-7500, The Netherlands*

[b] *Motor Control Laboratory, Department of Kinesiology, Group Biomedical Sciences, K.U. Leuven, Tervuursevest 101, Leuven B-3001, Belgium*

Accepted 18 December 2003

Abstract

A method to calculate the complete ground reaction force (GRF) components from the vertical GRF measured with pressure insoles is presented and validated. With this approach it is possible to measure several consecutive steps without any constraint on foot placement and compute a standard inverse dynamics analysis with the estimated GRF.

Keywords: Ground reaction forces; Pressure insoles; 3-D Gait analysis; Inverse dynamics

1. Introduction

Pressure insoles are measuring devices that record the pressure distribution under the foot sole. Although they have been used extensively in biomechanics of footwear (Giacomozzi et al., 2000), they have received little attention for the estimation of ground reaction forces (GRF) and its application point (Savelberg and de Lange, 1999), despite its potential for recording data during consecutive steps without imposing any constraints on feet placement. The errors in these estimates are due to temporal and spatial sampling (discrete number of sensors), and the fact that the forces are measured inside the shoe (Davis et al., 1996; Lord, 1997).

In this paper a method to estimate the complete GRF and their application point (AP) to be used in an inverse dynamics calculation is presented and validated.

2. Methods

2.1. Measurements

Five healthy subjects performed three valid walking trials at their natural cadence. The motion and GRF data were recorded with a video system (VICON 370, 5 cameras, 50 Hz) synchronized with two AMTI force plates (1000 Hz). The markers placement followed a standard protocol (Hayes) to define the Koopman's (1995) segment model. The same steps were recorded at 50 Hz with instrumented insoles Pedar© (Novel gmbh) in the subject's shoes. The insoles consist of an array (between 86 and 99 per insole) of pressure sensors (accuracy better than 5% and resolution of 1 N/cm^2). The vertical force and the centre of pressure (CoP) were estimated with the programs provided by Novel. The Medical Ethical Committee of the local Rehabilitation Hospital approved the experiment and the subjects signed an informed consent. A large number of trials (50%) were not valid due to: missing foot marker for more than one frame, foot not landing on the force plate and errors in the insoles recordings.

2.2. Insoles calibration

2.2.1. Transformation of the insoles reference frame to the global frame

The AP measured with the force plates was expressed in global frame coordinates while the CoP measured with the insoles was in the local frame of the insoles. During mid-stance both AP and CoP will be at the same position. The relation between both points is expressed as follows:

$$\underline{\hat{r}^{G}_{AP}}(k) = \underline{r^{G}_{OF}}(k) + \underline{\underline{R^{G}_{F}}}(k) \cdot (\underline{r^{F}_{OI}} + \underline{\underline{R^{F}_{I}}} \cdot \underline{r^{I}_{AP}}(k)), \qquad (1)$$

*Corresponding author. Motor Control Laboratory, Department of Kinesiology, Group Biomedical Sciences, K.U. Leuven, Tervuursevest 101, B-3001 Heverlee, Belgium.

E-mail address: arturo.fornercordero@flok.kuleuven.ac.be (A. Forner Cordero).

0021-9290/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2003.12.016

k represents time (either sample number or discrete time value), $\underline{r^G_{OF}}(k)$ and $\underline{\underline{R^G_F}}(k)$ are, respectively, the origin and rotation matrix of the foot frame (F) with respect to the global frame (G); both were calculated from the motion data. $\underline{r^F_{OI}}$ and $\underline{\underline{R^F_I}}$ are the unknown and constant origin and rotation matrix of the local insoles frame (OI) with respect to the local foot reference frame (F). $\underline{r^I_{AP}}(k)$ is the AP of the vertical GRF measured with the insoles in its local frame (I).

The coordinate calibration parameters $\underline{\underline{R^F_I}}$ and $\underline{r^F_{OI}}$ were constant if there was no change between the relative positions of the foot markers and the insoles. The AP of the GRF measured with force plates $\underline{r^G_{AP}}(k)$ was estimated with $\underline{\hat{r}^G_{AP}}(k)$ from Eq. (1)

$$\underset{\sim}{e} = \underline{r^G_{AP}}(k) - \underline{\hat{r}^G_{AP}}(k). \tag{2}$$

The optimal values of the six independent unknowns in Eq. (2), three from $\underline{r^F_{OI}}$ and three from $\underline{\underline{R^F_I}}$ (Cardan angles), were found by a least-squares minimization algorithm (Matlab, The Mathworks Inc.) of the over-determined set of non-linear equations constructed with five measured samples of $\underline{r^G_{AP}}(k)$ and $\underline{r^I_{AP}}(k)$. With these parameters, the left CoPl $\vec{r}_{\text{CoPl}}$ and right CoPr $\vec{r}_{\text{CoPr}}$ (measured with insoles) were translated into the global reference frame using Eq. (1) in subsequent trials.

2.2.2. Calibration of the vertical ground reaction force

It has been reported that there are differences between the first and the second vertical GRF peaks measured with insoles and force plates (Barnett et al., 2000). Therefore, the force signal was divided into three blocks containing the first and second maxima and the minimum of the vertical GRF. An independent linear regression calibration factor between insoles and force plates was calculated for each block.

2.3. Computation of the GRF

The resultant AP or total centre of pressure (CoP_{TOT}) was calculated from the individual centres of pressure of the right and left foot (CoPr and CoPl). The total reaction forces F_T and moment M_T with respect to CoP_{TOT} were computed from the motion data by inverse dynamics. They were related to the forces under each foot in Eq. (3) (the subscript error represents an imbalance of the model):

$$\begin{aligned}
&\vec{F}_\text{r} + \vec{F}_\text{l} = \vec{F}_\text{T} + \vec{F}_\text{Error},\\
&\vec{M}_\text{r} + \vec{M}_\text{l} + (\vec{r}_\text{CoPl} - \vec{r}_\text{CoPTOT}) \times \vec{F}_\text{l}\\
&\quad + (\vec{r}_\text{CoPr} - \vec{r}_\text{CoPTOT}) \times \vec{F}_\text{r} = \vec{M}_\text{T} + \vec{M}_\text{Error},
\end{aligned} \tag{3}$$

where $\vec{F}_\text{r}$, $\vec{M}_\text{r}$ and $\vec{F}_\text{l}$, $\vec{M}_\text{l}$ are the ground reaction forces and moments for right and left foot respectively. To estimate them, it was assumed that the vertical force determined CoP_{TOT}, Eq. (4)

$$\vec{r}_\text{CoPTOT} = \frac{F'_{y\text{l}} \cdot \vec{r}_\text{CoPl} + F'_{y\text{r}} \cdot \vec{r}_\text{CoPr}}{F'_{y\text{l}} + F'_{y\text{r}}}, \tag{4}$$

where $F'_{y\text{l}}$ and $F'_{y\text{r}}$ are the vertical GRF under each foot measured with the insoles. The factors ψ_r, and ψ_l represent the distance from CoP_{TOT} to CoPr and CoPl (Eq. (5)).

$$\psi_\text{r} = \frac{\|\vec{r}_\text{CoPl} - \vec{r}_\text{CoPTOT}\|}{\|\vec{r}_\text{CoPr} - \vec{r}_\text{CoPl}\|}, \quad \psi_\text{l} = \frac{\|\vec{r}_\text{CoPr} - \vec{r}_\text{CoPTOT}\|}{\|\vec{r}_\text{CoPr} - \vec{r}_\text{CoPl}\|}. \tag{5}$$

The solution to Eq. (6) was found with minimal error components

$$\begin{aligned}
&F_{y\text{r}} = \psi_\text{r} \cdot F_{yT}; \qquad F_{yl} = \psi_\text{l} \cdot F_{y\text{T}},\\
&F_{x\text{r}} = \psi_\text{r} \cdot F_{x\text{T}} + F_\text{corr} \cdot \cos\phi; \quad \text{and}\\
&\quad F_{x\text{l}} = \psi_l \cdot F_{x\text{T}} - F_\text{corr} \cdot \cos\phi,\\
&F_{z\text{r}} = \psi_\text{r} \cdot F_{z\text{T}} + F_\text{corr} \cdot \sin\phi; \quad \text{and}\\
&\quad F_{z\text{l}} = \psi_l \cdot F_{z\text{T}} - F_\text{corr} \cdot \sin\phi,
\end{aligned} \tag{6}$$

with $F_{y\text{T}}$, $F_{x\text{T}}$, $F_{z\text{T}}$ obtained from the motion data and the segment model parameters.

The correction force F_corr in the direction ϕ of the line joining CoPr to CoPl (Fig. 1) was modelled as a function of the total vertical GRF by least-squares fitting of a_i and b_i in the calibration trial (Eq. (7)).

$$\begin{aligned}
F_\text{corr}(k) = {} & a_1 \cdot F_\text{corr}(k-1) + a_2 \cdot F_\text{corr}(k-2)\\
& + b_1 \cdot F_{y\text{T}}(k) + b_2 \cdot F_{y\text{T}}(k-1) + b_3 \cdot F_{y\text{T}}(k-2)\\
& + b_4 \cdot F_{y\text{T}}(k+1).
\end{aligned} \tag{7}$$

3. Results

3.1. Vertical force and application point measurement

The root mean square error (RMS error) and the correlation coefficient (R) computed between the vertical forces measured with force plates and with insoles are presented for five subjects (Table 1).

The errors in Fy are below 10% and the correlation coefficient larger than 0.95. The RMS error of the CoP in the antero-posterior (X) direction is smaller than in the medio-lateral (M-L or Z) component. The centre of pressure calculated from the insoles is very similar to that of the force-plates (see Fig. 2). The largest part of

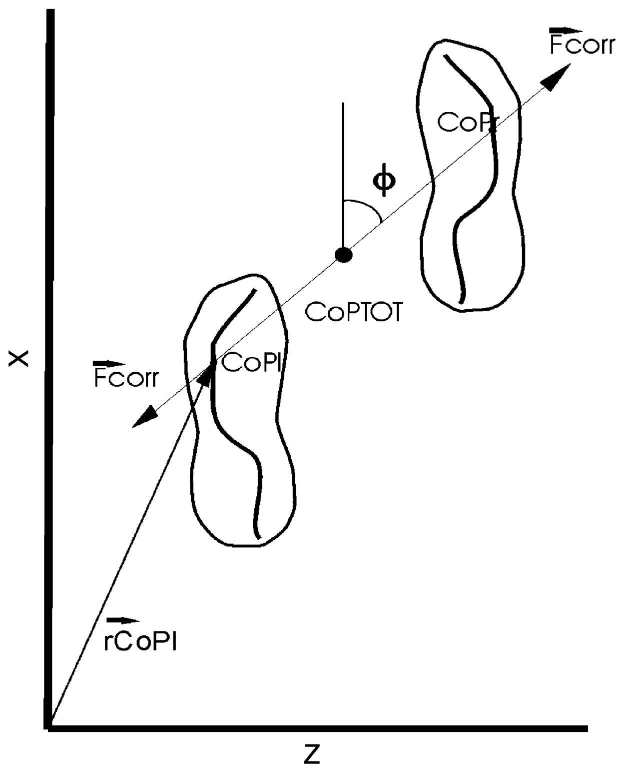


Fig. 1. Position of the centres of pressure of each foot CoP_r, CoP_l and the total CoP_{TOT}. The horizontal correction forces F_{corr} are of equal magnitude but opposite directions on each foot.

Table 1
Difference between the force plates and insoles measurement of vertical force and the centre of pressure: average and standard deviation of the RMS error (RMSERR) and average correlation coefficient (R) for all the subjects

Total label	RMSERR		R
	Mean	Std	
Fy (N)	41.2	15.1	0.962
CoP-X (m)	0.015	0.006	0.949
CoP-Z (m)	0.011	0.004	0.491

Fy is the vertical force, CoP-X and Z represent the centre of pressure in the antero-posterior and medio-lateral components, respectively.

the error in the CoP occurs at the beginning and the end of the foot.

3.2. Estimation of the GRF

The curves of the calculated forces are presented for the same typical case of one subject (Fig. 3). The time-axis ranges from the first heel-strike (left foot) till the last toe-off (right). However, the curves are plotted between first toe-off right until second heel-strike left because those events were not measured with the force plates.

Table 2 shows the RMS error and the correlation coefficient between the GRF measured with force plates (FP) and estimated (IN). The largest errors occur in the vertical component. Nevertheless, the relative value is small because the vertical forces are very large. The correlation coefficients are very high for the three force components. The larger errors occur at the beginning and at the end of the foot contacts, as can be seen in Fig. 3.

4. Discussion

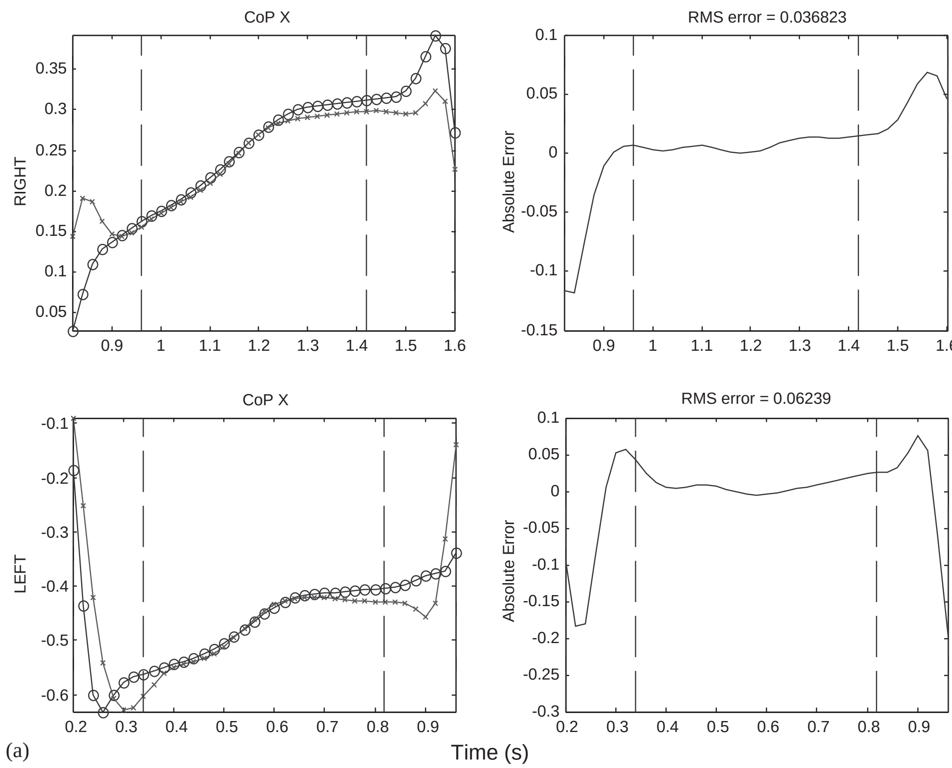
The motion data errors in the estimation of the foot segment origin influenced the error in the CoP position because the foot local frame was used to refer the insoles data to the global frame. Another method to locate the origin of the insoles consisted of chalking the footsole and measuring the footprint position on a force plate (Chesnin et al., 2000). The errors reported were not smaller (RMS error medio-lateral 0.56 ± 0.3 cm, and antero-posterior 1.37 ± 0.59 cm) than the ones presented here and it was impossible to measure several consecutive steps.

The largest error occurred in the antero-posterior CoP at heel-strike and toe-off instants. The one-segment model of the foot neglected the toe extension during the push-off phase before toe-off, explaining the large errors in these instants and revealing the need of a more complete foot segment model including the metatarso-phalangeal joint.

Despite all the drawbacks, the procedure presented here provides an estimation of the complete 3-D GRF from the motion and insoles data as a starting point of the inverse dynamics calculations. The main advantage of using insoles is that there is no constraint on foot placement and it is possible to measure several consecutive strides during gait, opening new fields for the analysis of gait (Dingwell et al., 2001).

Table 2
Difference in the 3-D GRF between the force plates and IN method: average and standard deviation of the RMS error (RMSERR) and average correlation coefficient (R) for all the subjects

	Right			Left		
	RMSERR (N)		R	RMSERR (N)		R
	Mean	Std		Mean	Std	
Fx antero-posterior (N)	7.53	1.32	0.979	9.15	1.80	0.977
Fy vertical (N)	27.84	7.40	0.997	30.13	8.70	0.995
Fz medio-lateral (N)	7.51	2.65	0.818	7.30	1.48	0.778



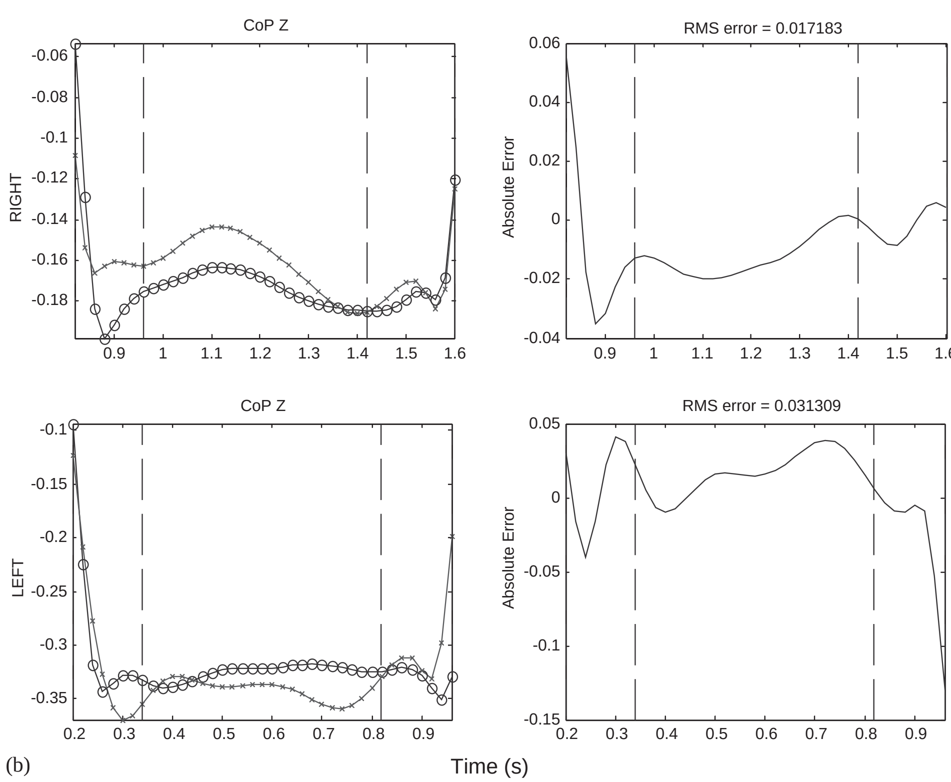


Fig. 2. Comparison of the CoP in the (a)antero-posterior and (b)medio-lateral direction plotted for each foot (upper: right, lower: left foot) between their respective heel-strike and toe-off, estimated from the insoles and motion data (line X) and the one measured with the force-plates (line O). The vertical lines indicate the contacts (toe-off and heel-strike) of the contralateral foot.

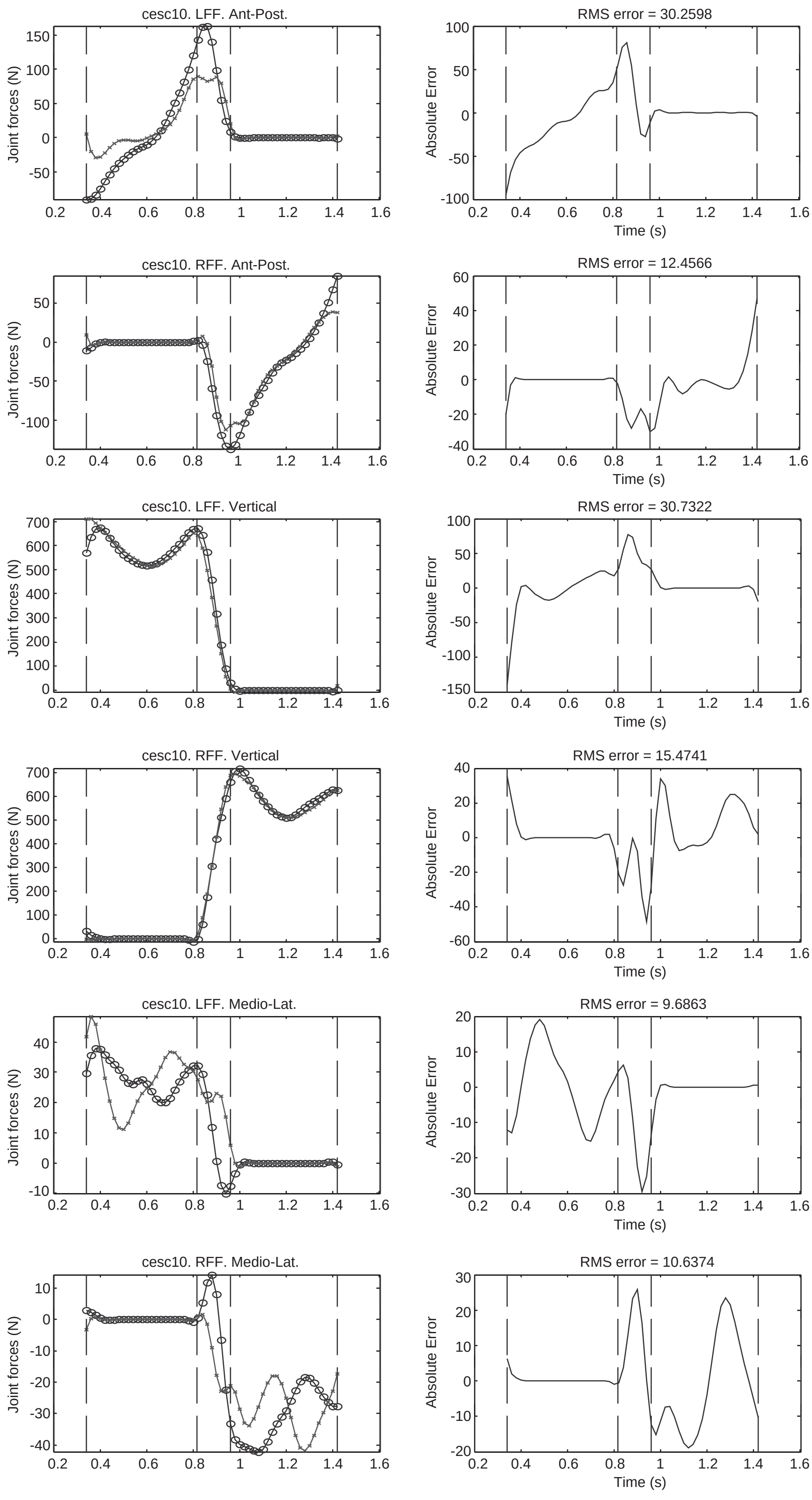


Fig. 3. Comparison of the estimated 3-D GRF from the IN method (solid line X) and the forces measured with the force-plates (dotted line O). The left and right GRF in the antero-posterior, vertical and medio-lateral (from top to bottom) directions are plotted from first right toe-off to second left heel-strike. The time axis and vertical lines are defined as in Fig. 2.

5. Conclusions

A new method to calculate the complete GRF information is presented and tested with pressure insoles. The main advantage of this method is the possibility of measuring consecutive steps with no constraint on foot placement. Therefore, with the complete GRF and the motion data it becomes possible to perform an inverse dynamics analysis. The error in the estimation of the horizontal ground reaction forces occurs mainly at the beginning and the end of the foot contacts. This procedure will improve as future developments in the pressure measuring insoles will result in more accurate data or in more complete measurements, e.g. horizontal forces.

Acknowledgements

We would like to thank the people from Roessingh R&D for their help in the experiments and J. Grady, M. Jannink and H. van Dijk for sharing the pressure insoles with us.

References

Barnett, S., Cunningham, J.L., West, S., 2000. A comparison of vertical force and temporal parameters produced by an in-shoe pressure measuring system and a force platform. Clinical Biomechanics (Bristol, Avon) 15, 781–785.

Chesnin, K.J., Selby-Silverstein, L., Besser, M.P., 2000. Comparison of an in-shoe pressure measurement device to a force plate: concurrent validity of center of pressure measurements. Gait & Posture 12, 128–133.

Davis, B.L., Cothren, R.M., Quesada, P., Hanson, S.B., Perry, J.E., 1996. Frequency content of normal and diabetic plantar pressure profiles: implications for the selection of transducer sizes. Journal of Biomechanics 29, 979–983.

Dingwell, J.B., Cusumano, J.P., Cavanagh, P.R., Sternad, D., 2001. Local dynamic stability versus kinematic variability of continuous overground and treadmill walking. Journal of Biomech Eng 123, 27–32.

Giacomozzi, C., Macellari, V., Leardini, A., Benedetti, M.G., 2000. Integrated pressure–force–kinematics measuring system for the characterisation of plantar foot loading during locomotion. Medical Biological Engineering Computing 38, 156–163.

Koopman, B., Grootenboer, H.J., de Jongh, H.J., 1995. An inverse dynamics model for the analysis, reconstruction and prediction of bipedal walking. Journal of Biomechanics 28, 1369–1376.

Lord, M., 1997. Spatial resolution in plantar pressure measurement. Medical Engineering Physics 19, 140–144.

Savelberg, H.H., de Lange, A.L., 1999. Novel Award Third Prize Paper. Assessment of the horizontal, fore-aft component of the ground reaction force from insole pressure patterns by using artificial neural networks. Clinical Biomechanics (Bristol, Avon) 14, 585–592.