ESTIMATING COMPLETE GROUND REACTION FORCES AND ANKLE JOINT TORQUES FROM PRESSURE INSOLE DATA IN WALKING AND RUNNING

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This study described a method to estimate complete ground reaction forces and ankle joint torques from only pressure insole sensor data. One subject performed 56 valid steps during heel-toe walking and running in canvas shoes at different speeds (0.85-4.00m/s). Motion data, ground reaction force data and plantar pressure data were simultaneously recorded. Six parameters of ground reaction forces and ankle joint torques were obtained, and were trimmed from touchdown to takeoff. Pressure values at each of the 99 sensors were used to predict these six parameters by linear stepwise regression. Prediction models with 80% or more explained variance were constructed. Estimated values were obtained from these models, and the prediction accuracy was reported. Comparison to a previously developed method was done.

KEY WORDS: kinetics, joint moment.

INTRODUCTION: Measurement of ground reaction forces during human motion is often constrained by the location and the number of force plates. Recently, Forner-Cordero et al (2004) developed a method to calculate the complete ground reaction forces during gait with pressure insole data. The calculated ground reaction forces were very accurate in vertical (R=.995-.997) and anterior-posterior direction (R=.977-.979), and were also good in medial-lateral direction (R=.778-.818). They then further employed inverse dynamics calculation with the kinetics information derived from this new method to obtain joint torques (Forner-Cordero et al 2006). The main advantage of this method was that it was possible to measure several consecutive steps and with no constraint on foot placement. However the method still relied on kinematics information for coordinate transform. Yet motion capture system can be moved to outdoor environment, it involves a little difficulty for the installation and calibration procedure. Therefore Forner-Cordero’s method is not yet really convenient in outdoor measurement.
This study described a method to estimate the complete ground reaction forces and ankle joint torques with only pressure insole data during walking and running at different speeds.

METHODS: One male subject (age = 27 yr, height = 1.74m, mass = 68kg) performed 58 trials with 56 valid steps (left: 28; right: 28) during heel-toe walking and running with canvas shoes at different speeds. A step was determined invalid if there were missing markers (1 trial), errors in pressure recording from insoles (1 trial), or with part of the foot landing out of the force plate (24 trials). The speeds were controlled by instructing the subject to walk and run with given rhythms (80, 120, 160 bpm for walking; 120, 160, 192 bpm for running) to achieve speeds of 0.85, 1.30, 1.66m/s in walking and 2.25, 2.60, 4.00m/s in running. Motion and ground reaction force data were recorded with an eight-camera VICON motion capture system and four AMTI force plates at 600Hz. Reflective markers were attached at anterior and posterior superior iliac spines, lateral femoral condyles, lateral malleoli, 2nd metatarsal heads and calcaneus at both left and right sides. Four more stick-mounted markers with base plates were attached at left and right thighs and shanks. Plantar pressure data were simultaneously recorded at 100Hz with Novel Pedar pressure insoles (model W) inserted in subject's shoes. There were 99 sensors in each insole, recording pressure data with a resolution of 2.50 kPa.

Motion data were imported to Visual 3D software (C-Motion, USA) for calculating ground reaction forces (anterior-posterior, medial-lateral, vertical) and ankle joint torques (dorsiflesion / plantarflexion, inversion / eversion, abduction / adduction). These six parameters were time-normalized in order to have data point in every 0.01s to match the sampling frequency of pressure data. The signs of these parameters were adjusted to make positive values mean forces in anterior / lateral / upward and torques in dorsiflexion / inversion / abduction directions. Every valid step was trimmed from touchdown to takeoff. Corresponding pressure values were used to predict the ground reaction forces and ankle joint torques separately by linear stepwise regression. Regression models with 80% or more explained variance (adjusted R2) were constructed and were chosen as the final prediction models. With the six final prediction models, the estimated ground reaction forces and ankle joint torques were calculated. Standard error of estimate and correlation coefficient of each of the 56 steps were obtained, and the mean values of left and right trials were reported. Comparison of prediction accuracy with Forner-Cordero's methods (2004, 2006) was done.

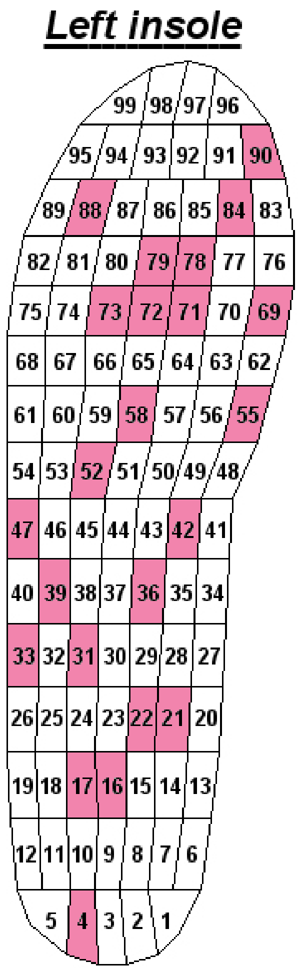

Figure 1: Figure 1 – Sensors in left insole (shaded are involved in models)

RESULTS AND DISCUSSION: In all six parameters to be estimated, there were models reaching an 80% explained variance. The prediction models were shown in Table 1. Figure 1 showed the locations of the 23 sensors involved in these six models. The prediction accuracy was quantified by the standard error of the estimate (SEE) and the correlation coefficient (R), as shown in Table 2.

Table 1 – Prediction models for the six parameters.

Parameter	**Prediction model**	**Adjusted R2**
Force (AP)	Fx(n) = 30.692 - 0.744(P16) - 2.083(P52)+ 0.205(P79) + 1.543(P88) + 1.099(P39)	.808
Force (LM)	Fy(n) = 2.445 - 0.222(P73) - 0.995(P22) - 0.716(P55) + 0.675(P42) - 0.111(P4) - 0.522(P21)	.803
Force (Z)	Fz(n) = 66.982 + 2.885(P58) + 3.464(P17) + 3.253(P71)	.931
Torque (DF/PF)	Tx(n) = -4.472 - 0.439(P71)	.903
Torque (IN/EV)	Ty(n) = -1.845 - 0.315(P69) - 0.293(P31)	.822
Torque (AB/AD)	Tz(n) = 0.286 + 5.124E-2(P72) - 9.19E-2(P33) + 5.925E-2(P47) - 5.45E-2(P36) + 6.085E-2(P84) - 5.63E-2(P78) - 1.07E-2(P90)	.803

(* Unit: force in N, torque in Nm. PX is the value of pressure in kPa of the pressure sensor number X.)

Table 2 – Standard Error of the Estimate (SEE) and the correlation coefficient (R) between the measured and the predicted parameters for all 56 analyzed steps.

	This study				**Forner-Cordero's studies**			
	Left		**Right**		**Left**		**Right**	
Parameter	SEE	R	SEE	R	SEE	R	SEE	R
Force (AP)	33.53 (14.52)	.920	32.95 (15.12)	.929	9.15 (1.80)	.977	7.53 (1.32)	.979
Force (LM)	11.79 (4.24)	.914	10.62 (4.25)	.923	7.30 (1.48)	.778	7.51 (2.65)	.818
Force (Z)	74.92 (48.08)	.974	79.81 (38.45)	.960	30.13 (8.70)	.995	27.84 (7.40)	.997
Torque (DF/PF)	7.54 (4.77)	.973	7.15 (3.70)	.980	5.76 (13.65)	.984	5.70 (10.10)	.980
Torque (IN/EV)	6.00 (4.17)	.960	4.58 (1.90)	.898	5.45 (8.34)	.545	3.58 (1.83)	.756
Torque (AB/AD)	1.55 (0.94)	.871	1.09 (0.38)	.968	3.97 (0.95)	.867	3.16 (5.14)	.855

(* Unit: force in N, torque in Nm.)

When compared with Forner-Cordero's studies (2004, 2006), the results from this study was generally less accurate as indicated by a larger SEE value. Figure 2 showed the pattern of real and predicted data in one trial of left foot contact during walking at a speed of 0.83m/s. Yet the results in this study were good and with high correlation coefficient (R=.871-.974), we do not know if the method can be generalized to other motions, subjects, equipment system and other factors. For practical use, we suggest letting the subject perform the testing motion in laboratory first, in order to develop specific equations for estimation. Moreover, other regression model can also be chosen for specific test according to the desired accuracy.

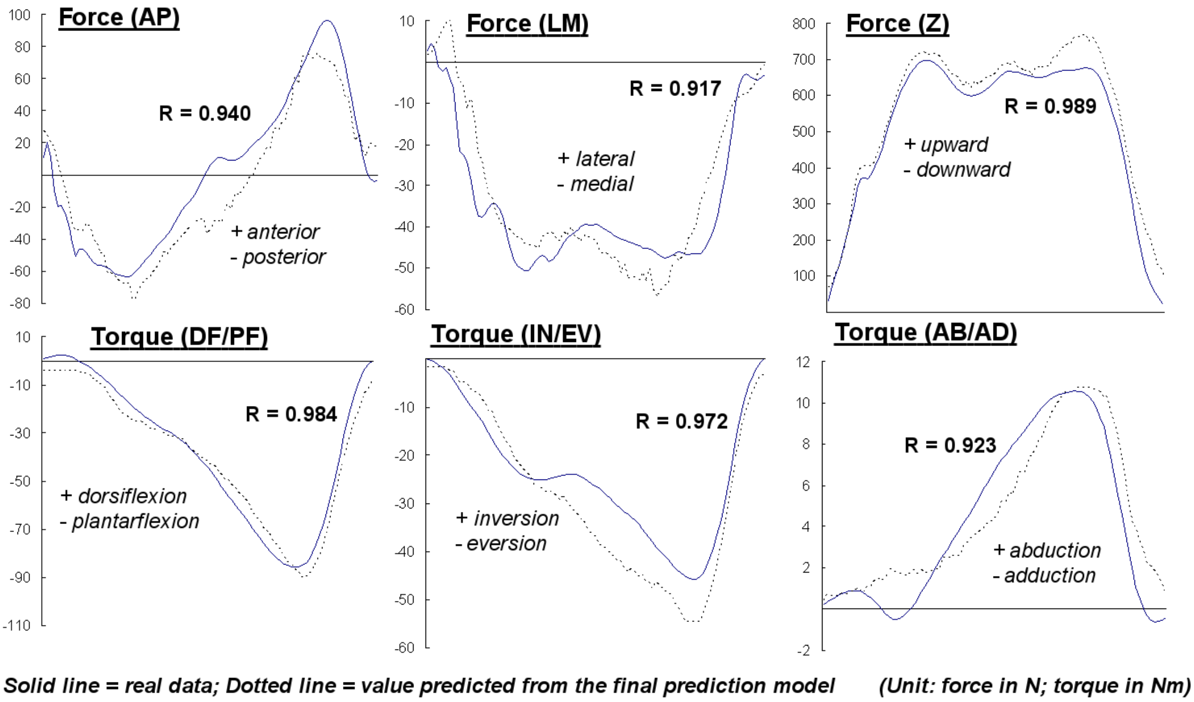

Figure 2 – Real and predicted data in left foot contact during walking at a speed of 0.83 m/s.

CONCLUSION: This study presented a method to estimate complete ground reaction forces and ankle joint torque with only pressure insole data during walking and running. Further studies should reveal if the method can be generalized to different motions, subjects, insole systems and footwear.

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