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Ambulatory assessment of 3D ground reaction force using plantar pressure distribution

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ABSTRACT

This study aimed to use the plantar pressure insole for estimating the three-dimensional ground reaction force (GRF) as well as the frictional torque (T_F) during walking. Eleven subjects, six healthy and five patients with ankle disease participated in the study while wearing pressure insoles during several walking trials on a force-plate. The plantar pressure distribution was analyzed and 10 principal components of 24 regional pressure values with the stance time percentage (STP) were considered for GRF and T_F estimation. Both linear and non-linear approximators were used for estimating the GRF and T_F based on two learning strategies using intra-subject and inter-subjects data. The RMS error and the correlation coefficient between the approximators and the actual patterns obtained from force-plate were calculated. Our results showed better performance for non-linear approximation especially when the STP was considered as input. The least errors were observed for vertical force (4%) and anterior–posterior force (7.3%), while the medial-lateral force (11.3%) and frictional torque (14.7%) had higher errors. The result obtained for the patients showed higher error; nevertheless, when the data of the same patient were used for learning, the results were improved and in general slight differences with healthy subjects were observed. In conclusion, this study showed that ambulatory pressure insole with data normalization, an optimal choice of inputs and a well-trained nonlinear mapping function can estimate efficiently the three-dimensional ground reaction force and frictional torque in consecutive gait cycle without requiring a force-plate.

1. Introduction

Three-dimensional (3D) ground reaction force (GRF) composed by three components, i.e., anterior–posterior (F_{AP}), medial-lateral (F_{ML}) and vertical (F_V), as well as frictional torque (T_F) are often used in the lower limb joint moments and powers calculation [1] and is a significant indicator in clinical evaluations [2–4]. 3D GRF is generally measured by force-plate, which is often limited to a single stance during gait. Instrumented shoes by force and moment sensors under the foot [5] and 3D pressure measuring insoles using different sensor technologies [6–8] were used for this purpose. However, thick insoles or shoes might alter the normal gait pattern and the original interface between shoe and ground [9] and limit the use of such systems in clinical applications.

The measurement of plantar pressure (PP) distribution is now possible by commercial platforms or thin insoles integrating matrices of load cells and is used widely for clinical evaluation [10,11] and biomechanical studies [12,13]. However, existing pressure insoles for ambulatory measurement of PP distribution are only sensitive to vertical forces acting on the insole, which limits their use for 3D GRF estimation. Although PP distribution could be related to normal and shear stresses in the subsurface of foot [14], the complex behavior of the soft tissue of foot sole [15,16] avoids finding a simple mathematical model of the shear GRF or the friction torque from PP distribution. Commercial pressure insoles accompanied by camera-based motion capture system were used for estimating the 3D GRF instead of force-plate [1]. Despite the good estimation of 3D GRF, the technique remains limited to laboratory environment due to the use of camera. The relationship between PP in eight area of foot and anterior-posterior GRF in healthy subjects was investigated using a neural network [17]. Subsequently, the complete GRF was estimated in young healthy subjects using a stepwise linear regression on 99 pressure elements in insole [9]. Both latter studies showed the possibility of predicting 3D GRF from PP data. However, they did not investigate how to optimally remove the redundancy of PP data and enhance

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the force-plate are needed for training phase. However, the use of camera-based system is not mandatory. Actually, the camera was used only for aligning the shear components (F_{AP}^{FP} and F_{ML}^{FP}) recorded by force-plate in insole frame for accurate comparison purpose and not as an input of the model. Expressing the shear forces in horizontal plane is also possible without motion capture and by matching the COP measured by force-plate to COP measured by insole during training phase.

According to our analyses, the ground reaction force and the frictional torque during walking could be estimated using the plantar pressure distribution of commercial ambulatory pressure insoles. Comparing to a gold standard (force-plate) a nonlinear mapping function with an optimized structure provided the best results for both healthy subjects and patients. The mapping function in this estimation could be even found based on the data of other subjects. However, better performance was obtained when the estimation was calibrated for the same subject. Our algorithm is suggested for further validations with larger number of subjects to show the efficiency of this technique in clinical evaluation of the ground reaction force and further assessments of joint force and moment.

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Conflict of interest

None.

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