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Ambulatory measurement of ankle kinetics for clinical applications

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ABSTRACT

This study aimed to design and validate the measurement of ankle kinetics (force, moment, and power) during consecutive gait cycles and in the field using an ambulatory system.

An ambulatory system consisting of plantar pressure insole and inertial sensors (3D gyroscopes and 3D accelerometers) on foot and shank was used. To test this system, 12 patients and 10 healthy elderly subjects wore shoes embedding this system and walked many times across a gait lab including a force-plate surrounded by seven cameras considered as the reference system. Then, the participants walked two 50-meter trials where only the ambulatory system was used.

Ankle force components and sagittal moment of ankle measured by ambulatory system showed correlation coefficient (R) and normalized RMS error (NRMSE) of more than 0.94 and less than 13% in comparison with the references system for both patients and healthy subjects. Transverse moment of ankle and ankle power showed $R>0.85$ and NRMSE $<23\%$. These parameters also showed high repeatability (CMC >0.7). In contrast, the ankle coronal moment of ankle demonstrated high error and lower repeatability. Except for ankle coronal moment, the kinetic features obtained by the ambulatory system could distinguish the patients with ankle osteoarthritis from healthy subjects when measured in 50-meter trials.

The proposed ambulatory system can be easily accessible in most clinics and could assess main ankle kinetics quantities with acceptable error and repeatability for clinical evaluations. This system is therefore suggested for field measurement in clinical applications.

1. Introduction

Ankle moment is usually measured in a laboratory equipped with stationary devices, e.g., cameras and force-plate (MacWilliams et al., 2003). However, using stationary devices has some drawbacks. First, the measurement is constrained by the area of the laboratory which limits the number of consecutive strides. Second, the subjects need to step with their feet completely on force-plate which might affect natural gait (Forner-Cordero et al., 2006; Schepers et al., 2007). Considering the importance of ankle kinetics for outcome evaluation of ankle treatments (Valderrabano et al., 2007; Ingrosso et al., 2009), there is a need for an ambulatory system that can be used outside a laboratory yet in a clinical environment without hindering the patient's gait.

In the past, ambulatory systems were proposed to measure orientation of body segments using inertial measurement units (IMU) (Favre et al., 2008). On the other hand, instrumented shoes have been suggested for ground reaction force (GRF) measurement since the 1970s based on different sensors technologies (Miyazaki and Iwakura, 1978; Faivre et al., 2004; Zhang et al., 2005; Bae et al., 2011). However, a few studies developed shoes for 3D GRF measurement (Spolek and Lippert, 1976; Kljajic and Krajnik, 1987; Hosein and Lord, 2000; Razian and Pepper, 2003; Veltink et al., 2005). These works implemented 3D force sensors in shoe sole which thickened it and may have perturbed the natural gait. Besides, the long-term performance of these shoes was not evaluated. Finally, these shoes were prototypes that were not accessible in many clinics.

Unlike foot kinematics and 3D GRF, the algorithms for ambulatory assessments of ankle moments are still lacking. Schepers et al. (2007) used shoes equipped with 3D force sensors beneath the outsole (Veltink et al., 2005) and IMUs to assess ankle moments. This system later allowed estimation of center of mass displacement and was tested for stroke patients (Schepers et al., 2009). However, such instrumented shoes may change the normal foot–ground interface or perturb the natural gait (Liedtke et al., 2007) and might not be easily accessible for clinical uses. Recently, we have proposed a method to estimate 3D GRF and frictional torque based on vertical pressure distribution measured

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