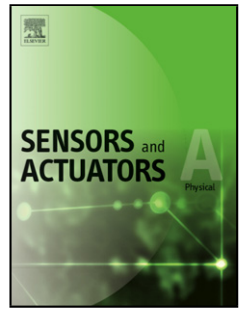

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Wearable Inertial Sensor based Parametric Calibration of Lower-limb Kinematics

Myeongkyu Kim and Donghun Lee

Abstract

In this study, the calibrations of the lower-limb kinematics based on the five wearable IMU sensors were performed to reduce the inherent kinematic errors due to the both incorrect measurements of the kinematic parameters and the uncertainties of the geometric modeling of the lower-limb joints. Unlike the actual body structure, the ankle and knee joint of the lower-limb part are generally modeled as pure revolute joints of two or three degrees of freedom with some assumptions. However, it is obvious that these mismatches in the simplified geometrical modeling of the joint in the lower-limb kinematics lead to uncertainties in the model-based 3D motion tracking of human body such as walking velocity estimation, gait analysis, etc. As main research contributions, we intended to examine exactly which error factors are responsible for the kinematic uncertainties that arises from the 3D motion tracking based on the lower-limb kinematics and wearable IMU sensors. The lower-limb kinematics model in this research assumes that the ankle, knee, and hip joints are all three degrees of freedom, and that the three principle axes at each joint may not intersect at a common point. That is, the kinematic uncertainties included in the joint model will be confirmed by performing a kinematic calibration taking into account the orientation of joint axes and joint offsets as kinematic error parameters as well as the case of only calibrating the link lengths. This study also uses a new calibration plate with seven sole-shaped jigs and five wearable IMU sensors to measure the actual pose of the right foot, which is the distal end of the lower-limb kinematics with respect to the left foot. In order to secure an in-depth insight into the wearable IMU sensor based calibrations of the lower-limb kinematics, the seven sole-shaped jigs were designed to independently allow the right foot on those jigs to have predefined 3-dof poses. Finally, an iterative least square method is adopted to minimize the error between the nominal kinematic model-based pose and the actual poses of the right foot with respect to the left foot on the calibration plate. In an experiment with one subject, the reduction rate of the position error depends on the measurement of the initial kinematic parameters, but the RMS position error of the right foot relative to the left foot was improved by 336.1% from 36.5mm to 11.3mm.

Keywords: Lower-limb kinematics, parametric calibration, inertial measurement unit, iterative least-squares, POE formula

1. Introduction

In recent decades, 3D motion tracking technology has become increasingly important in the fields of biomedical engineering, sports, military, etc. and enormous studies have been conducted to improve precision of the human body kinematics, which is the most important for acquisition of accurate motion capture data [1, 2, 3]. The calibration of kinematics model is a process to minimize the uncertainties in the kinematics model due to the incorrect measurements of the human kinematic parameters [1].

That is, the kinematic calibration is a way that minimizes the difference between the nominal and the actual human kinematic model [4, 5]. In the field of robotics, the revolute and prismatic joint is used for joint modeling of the robotic manipulators [6, 7]. In the case of the lower-limb kinematics in biomechanics fields, the ankle is modeled as a hinge joint of 1- or 2-dof, the knee as a condyloid joint of 2-dof, and the hip joint as ball-and-socket joint of 3-dof, respectively [8]. However, as shown in Fig. 1-(a), the ankle joint is a joint of very complex geometry composed of distal tibiofibular joint, tibiotalar joint, and fibulotalar joint. Thus, if plantar flexion and dorsiflexion in the ankle is modeled as pure revolute joint of 1-dof, ambiguous measurement errors will occur in kinematic model-based biomechanical analysis. Fig. 1-(b) depicts principle of the motion in the knee joint. Since the shape of the femoral condyle in contact with the tibial plateau of the tibia is elliptical, slight translation at the center of rotation occurs during flexion and extension. Fig. 1-(c) shows the structure of the hip joint. The head of the femur is relatively stable compared to the ankle and knee joints because it is fixed to the joint capsule in contact with the surface of the concave acetabulum. Therefore, when building the kinematic model, it is necessary to pay close attention to the kinematic error parameters existing in the ankle and knee joints.

Recently, I-Ming Chen [1], Min Su Lee [9], and Charlton [3], who performed studies on human body kinematics, modeled the ankle, knee, and hip joints of the lower-limb part as a 3-dof spherical joint. As a result of Charlton's optical motion capture system based gait analysis [3], the dorsi and plantar flexion in the ankle