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Original Research Article

Wearable acceleration sensor application in unilateral trans-tibial amputation prostheses

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ABSTRACT

The availability of human walking gait data collected from the wearable acceleration sensors for trajectory control of an active artificial ankle joint in the unilateral trans-tibial prosthesis was investigated in this study. It is observed that the collected acceleration data can be used in the rulebased control of the prosthetic leg. A portable microprocessor-based data acquisition system, and data transfer module were designed for capturing the acceleration signals during walking. Flexionextension angle pattern of ankle joint was determined from acceleration signals of two tri-axial wearable accelerometers placed on the shank and foot segments. This pattern was utilized for control of the active artificial ankle joint in the trans-tibial prosthesis. This approach may have the potential of contributing the development of better prostheses.

1. Introduction

Mobility of the lower extremity amputees relies very much on the prostheses. Control algorithms for robotic ankle systems in lower-limb orthoses, prostheses, and exoskeletons were reviewed in [1]. Andrysek provided a review for lower-limb prosthetic technologies developed in last two decades [2]. Martins et al. reviewed the state of the art in the robotic technology for mobility assistive devices developed for people with disabilities [3]. They presented the important role of the robotics in mobility of the assistive devices existing on the literature, with the particular focus on the walking technologies.

The researches in relation to the ankle joint behavior show that the ankle joint can be replaced effectively with passive mechanical devices [4]. Many persons using trans-tibial prostheses with passive mechanical ankle-foot systems can walk with the gait patterns very closed to the able-bodied walkers at the slow walking speeds. One of the reasons making this possible is that the ability of the amputees to compensate for shortcomings of their prostheses reduces observable differences. Nevertheless, the actively controlled prosthetic systems are necessary to mimic the ankle characteristics during walking at fast walking speeds and for other activities rather than level walking.

In order to remove insufficient features of passive assistive devices, researches are being maintained for developing actively controllable lower extremity orthoses [5], and prostheses such as Belgrade leg [6], an actively controlled above-knee prosthesis [7], Series Elastic Actuator [8,9], Sparky leg by Thomas G. Sugar's laboratory at Arizona State [10,11], and active below and above knee prostheses by Michael Goldfarb's laboratory at Vanderbilt [12,13]. Some trajectory control methods with rule-based control approach developed by sensor signals and previously acquired walking gait data are implemented for control of these active prostheses. On the other hand, it could be an interesting point for researchers that

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the sound leg of the unilateral lower extremity amputee provides a very valuable data source in preparing procedure of rule-based control approach for control of the active prosthetic legs. Therefore, this study depends on the principle of that the acceleration data obtained from the sound leg can be used for the control of the prosthetic leg.

The main method for gait analysis is the tracking of a subject's movement through camera and force plate systems. These systems can provide position data of body segments, but these systems are usually used in laboratories. An alternative method for providing gait analysis and gait posture estimation potential is to use wearable acceleration sensors placed on the segments of human body for monitoring walking gait. Use of the wearable acceleration sensor systems was first proposed by Morris [14]. These systems have advantages over camera-based systems because of the measurements can be conducted outside the laboratories to monitor daily living activities. Bouten et al. performed a study for assessment of daily physical activity with an accelerometer and portable data processing unit [15]. They reported that the shortcomings of the system are its low sensitivity to sedentary activities, and the inability to register static exercise. Bussmann et al. used an ambulatory acceleration system to quantify motor behavior in patients after back surgery [16]. They made continuous ambulatory registrations of signals based on the acceleration sensors mounted on patients performing a number of functional activities in and around their own houses. They reported that ambulatory activity monitoring, which is an instrument based on long-term ambulatory monitoring of accelerometer signals to assess several physical activities during normal daily life, can be used to obtain insight into actual behavior in the treatment of patients with pain. Foerster et al. made a study for detection of posture and motion by accelerometers [17]. They used sensor placements for the subjects acting postures/motions outside the laboratory according to a standard protocol. They reported that the detection of posture and motion with an acceleration signal-based analysis system is highly reliable.

Wearable sensors systems cannot provide position data, but only information such as the tilt angle of a body segment, compared to camera systems. Therefore, many works using wearable sensors have been limited to just comparing acceleration data or monitoring gait events. Kavanagh et al. examined the effect of aging on the pattern and structure of head and trunk accelerations during walking [18]. They made some comparisons between the experimental results related the head and trunk acceleration measuring of young and elderly individuals using tri-axial accelerometers. Jasiewicz et al. performed gait event detection study, which is related with the determination of the timing of the toe-off and heel contact moments, by using miniature linear accelerometers and angular velocity transducers in comparison to using standard pressure-sensitive foot switches, in able-bodied and spinal-cord injured individuals [19]. Lau and Tong investigated the reliability of using accelerometer and gyroscope for gait event identification on persons with dropped foot [20]. They used three sensor units attached at the thigh, shank and foot of the impaired leg of the subjects with dropped foot. They described a threshold detection method for identifying gait events.

Some works investigated the use of acceleration sensors for obtaining body segment posture and orientation [21,22]. They used a combination of acceleration and gyro sensors because the acceleration sensors were not suited for long-term measurements due to error accumulated according to time. The displacement of these sensors on the thigh and shank were used to estimate knee joint angles during walking. Takeda et al. proposed a novel method for measuring human gait posture using wearable acceleration sensor units [23]. They measured the angular velocity and acceleration during walking with sensor units worn on the abdomen and the lower limb segments. They reported that this method provides important information for gait diagnosis. In another study, they also proposed a gait posture estimation method that can measure the three-dimensional positions of joint centers [24]. They calculated the flexion–extension joint angles of the hip and knee joints of the healthy subjects and compared with a camera motion capture system. Lim et al. designed and assessed a wearable sensing system including an accelerometer for capturing human arm postures in rehabilitation [25]. Yuan and Chen introduced a method to use the inertial sensor system to track the velocity and the dynamic behavior of a person [26].

Some other works have investigated the use of acceleration sensors for the purpose of gait pattern recognition. Gafurov and Snekkenes investigated the gait biometric as a new biometric that is better suited in some applications compared to the traditional ones, such as fingerprint, iris, face and voice, and complement them for improving security and usability [27]. They presented an alternative approach based on analyzing the body segments' motion signals collected by using wearable sensors, for person recognition purposes. They reported that the analyses of the acceleration signals obtained from ankle, hip, trousers pocket, and arm indicate some promising performances in verification of user identity. They provided some new insights toward understanding the uniqueness and the discriminative properties of the gait in case of ankle/foot motion with respect to the shoe attribute, axis of the motion, and gait cycle parts. Rong et al. tested the gait of healthy subjects walked naturally, by using portable microprocessor-based data acquisition systems having a tri-axial accelerometer [28]. They have realized some comparisons between the template data set and the verification samples generated from the obtained gait data of the walking trials. They have found that it is possible to recognize the people based on their gait acceleration signals. Hang et al. have proposed a novel gait recognition method for biometric applications [29]. They demonstrated the potential of the proposed approach by using the gait patterns determined via knee acceleration signals.

2. Actuator

In addition to the above, another biometric application area of the wearable acceleration sensors is to provide an alternative data source for preparing control strategies of active lower extremity prostheses. In human walking, information obtained from various biological sensors is integrated, and motor commands are created to produce adaptive and efficient