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Technical note

A foot-wearable interface for locomotion mode recognition based on discrete contact force distribution

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ABSTRACT

The knowledge of plantar pressure distribution is important in understanding human locomotion activities, and its integration with robotic assistive devices is an important potential application. In this paper, we aim to explore the potential of using discrete contact force distribution signals for locomotion mode recognition. A foot-wearable interface comprising a pair of sensing insoles, each with four sensors at selected locations, has been designed to record discrete contact forces during locomotion. Based on the information of discrete contact force distribution, we present a locomotion mode recognition strategy with decision tree and linear discriminant analysis classifiers. To verify the measurement performance of the sensing system, experiments are carried out to investigate the system stability in long term working conditions and its adaptation to different ground surfaces. To evaluate whether discrete contact force signals can be used for locomotion mode recognition, five able-bodied subjects and one amputee subject are recruited and asked to perform six types of locomotion tasks. With the proposed recognition strategy, reliable recognition performance is obtained. The average classification accuracy is 98.8% ± 0.5% for able-bodied subjects and 98.4% for the amputee subject, which is comparable to those obtained from systems based on other sensors. These experimental results indicate that monitoring of discrete contact force distribution is valuable for locomotion mode recognition. Its use can be combined with other sensing systems to achieve better performance of locomotion mode recognition for intelligent assistive device control.

1. Introduction

Plantar pressure distribution reveals detailed information about foot contact, which is of great value for human gait analysis. Compared with platform based measurement systems (e.g. force plate), wearable contact force sensing systems (e.g. in-shoe sensors) are more portable and convenient for long-term measurement of daily activities, especially in outdoor environments. They allow wider applications with respect to abnormal gait analysis, footwear design, and terrain performance [1]. Various commercial products such as F-Scan® by Tekscan [2], Pedar® by Novel [3] and prototypes of foot wearable measurement systems [1,4–13] have been proposed with various applications in sports and gait monitoring. Though wearable plantar pressure measurement systems have already been applied in many fields, there are still potential application spaces in other areas.

One possible application of wearable contact force measurement systems is its integration with robotic assistive devices, e.g. powered lower-limb prostheses. Most current locomotion assistive robots are controlled by finite state machine (FSM) models. Each locomotion mode (e.g. level-walking and stair ascent) has its own control strategy. To better assist humans and achieve natural gait patterns with less energy consumption, these advanced assistive devices should first "know" human movement intentions and then select the appropriate control mode [14–16]. Therefore, locomotion mode recognition is an important issue for robotic assistive device control. Signals used for locomotion mode recognition can be roughly divided into two main categories. The first category includes bioelectric signals related to human movement, with electromyography (EMG) being the most widely used for locomotion mode recognition [17–19]. Huang et al. proposed a phase-dependent recognition system to recognize seven locomotion modes using surface EMG signals of lower-limb muscles. The average classification accuracy was 92.2% for able-bodied subjects and 91.6% for amputee subjects. Human body capacitance sensing, which detects leg shape changes caused by

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muscle contractions during locomotive movements, provides another signal for movement recognition with comparable accuracy [20,21]. In [21], 10 channels of capacitance signals measured from the lower limb were used to recognize six locomotion tasks. Average recognition accuracies for able-bodied subjects and amputee subjects were 93.6% and 93.4%, respectively. However, for both EMG and capacitance signal measurement, electrodes should directly contact skin, which may cause inconvenience and discomfort. The other kind of sensors used for locomotion mode recognition are on-board mechanical sensors, which includes gyroscopes, accelerometers, goniometers and magnetometers [22–24]. Varol et al. presented a real-time recognition approach based on prosthesis-implemented sensors. Signals measuring joint angles and angular velocities of the knee and ankle, socket sagittal plane moment, foot forces of heel and ball were collected to realize the recognition of three locomotion modes (standing, sitting, and walking) and transitions between them [22]. However, these signals usually vary with accumulated errors or time-related drifts. To realize satisfactory and reliable recognition performance, classification methods based on multi-sensor fusion were developed in recent years. Huang et al. proposed an EMG-mechanical fusion approach, and obtained much better recognition performance than using only mechanical or EMG signals [25]. Therefore, it is meaningful to add more useful movement information to existing locomotion mode recognition systems in order to further improve the performance. Plantar pressure distribution contains rich information on human gait. However, most existing prosthesis-implemented and orthosis-implemented contact force measurement systems are only used for the detection of gait events or gait phases [26–31]. To our knowledge, no previous studies have investigated whether the information of contact force can be used to recognize multiple locomotion tasks (e.g. standing, level-ground walking, stair ascent, and stair descent) for robotic assistive device control.

In this paper, we explore the potential of using plantar pressure distribution information for human locomotion mode recognition. To make a systematical analysis, we design a foot-wearable interface, which is comprised of a pair of sensing insoles and transmission circuits. Each of the sensing insoles is integrated with four force sensors to measure discrete contact force distribution signals. To evaluate whether discrete contact force signals can be used for locomotion mode recognition, we propose a classification strategy based on decision tree analysis and linear discriminant analysis, and off-line recognition analysis is performed. To verify the measurement performance of the proposed system, experiments are carried out to investigate system stability of long term working on and adaptability to different ground surfaces. Five able-bodied subjects and one transtibial amputee subject are recruited and asked to perform six types of locomotion tasks, which include sitting, standing, walking, obstacle clearance, stair ascent, and stair descent. Satisfactory recognition performances are obtained for both able-bodied subjects and the amputee subject. These results indicate that discrete contact force distribution signals do provide valuable information for human locomotion mode recognition, and the proposed system can be combined with existing recognition systems based on other sensing information to obtain better recognition performance.

The rest of this paper is organized as follows. Section 2 describes the measurement system in detail. Section 3 presents the locomotion mode recognition strategy. Experiments and results are described in Section 4. The conclusion is made in Section 5.

2. Discrete contact force distribution measurement system

We presented a foot-wearable interface for locomotion mode recognition based on discrete contact force distribution. The interface was composed of a pair of sensing insoles, signal process circuit modules, and a base station connected to a host computer (Fig. 1(a)). Discrete contact force distribution is measured by sensing insoles placed in users' shoes. The signal processing module transmits signals to the base station via wireless. The base station rearranges signal sequences measured from different feet, and then transmits the data to the host computer.

Force sensors placed on sensing insoles are used to measure discrete contact force distribution. To fit users with differently sized feet, sensing insoles with different sizes are prepared in advance.

2.1. Sensing insole

2.1.1. Sensor placement

Though plantar pressure distribution of the whole foot contains richer information, discrete contact force distribution might be enough to investigate certain foot functions during walking and other locomotion activities [32]. To collect sufficient information for locomotion mode recognition with fewer force sensors, properties of plantar pressure distribution are analyzed to guide the placement of force sensors.

In this research, the method used for investigating contact forces of different foot sole zones is similar to the one used in our previous work [33]. Plantar pressure distribution of the whole foot is measured with a force plate, *footscan® advanced* & *hi-end system* (RSscan, Inc.,). The plate is 2 m × 0.4 m in size, with a sensor density of about $2.7 \times 10^4/\mathrm{m}^2$. Each sensor embedded in the plate has a size of 0.005 m (lateral) × 0.007 m (anterior–posterior). Three able-bodied subjects and one unilateral transtibial amputee subject (left side amputated) were asked to walk on the plate without wearing shoes. The amputee subject walked with his own prosthetic foot (Otto bock 1S90). Contact force distribution of each step was measured by the plate automatically, and the sampling rate was 250 Hz. In this experiment, each subject was required to walk through the force plate for 5 times. The entire plantar pressure distribution area was divided into 10 zones (Fig. 2(a)). Fig. 2(b)–(e) shows the contact force distribution of the amputee subject and one of the able-bodied subjects. We can notice that the contact force distribution of the prosthetic foot is not exactly the same as the intact foot, probably due to the absence of ankle and toe joints. However, contact force distributions of prosthetic feet and intact feet might share common biomechanical characteristics.

Contact force distribution data of each zone within each step were calculated for each subject, and principal component analysis (PCA) was performed. Results showed that the variance ratio contributions of the first two principal components for all the subjects were above 90%. Then the absolute values of the loading coefficients of different zones in the first two principal components were compared, and *Z 1, 6, 9, 8* were found as the four largest when compared overall. These four zones made more contributions than the other zones in the first two principal components.

Thus, we selected these four zones as the positions for sensor placement. The four zones were defined as follows: (a) under the calcaneus tuberosity (*Z 1*); (b) under the fourth metatarsal (*Z 6*); (c) under the first metatarsal (*Z 8*); and (d) under the hallux (*Z 9*). However, the shape of an insole is not exactly the same as human foot. The positions of force sensors on an insole were empirically determined (Fig. 1(b)).

2.1.2. Force sensors

When the foot-wearable measurement system is used during walking, subjects do not expect to feel any discomfort. Therefore, the size, thickness and transmission model should be considered for force sensor selection. The size of the force sensor is limited by the size of the foot. A coin-size force sensor would be appropriate, as its contact region is large enough to guarantee quality signal measurement