Robotics and Autonomous Systems 75 (2016) 50–59

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Recognition of gait cycle phases using wearable sensors

Samer Mohammed [a,*], Allou Samé [b,1], Latifa Oukhellou [b,2], Kyoungchul Kong [c,3], Weiguang Huo [a,4], Yacine Amirat [a,4]

[a] University Paris Est, Créteil (UPEC), LISSI, 122 rue Paul Armangot, 94400, Vitry-Sur-Seine, France
[b] University Paris-Est, IFSTTAR, COSYS-GRETTIA, F-77447 Marne-la-valle, France
[c] Department of Mechanical Engineering, Sogang University, Seoul, Republic of Korea

HIGHLIGHTS

- This paper deals with the detection of the main characteristics of the gait phases.
- A segmentation of the human body COF is done using the in-shoe pressure mapping system.
- Identification of the gait phases is done using a regression model.
- The proposed method has the advantage of detecting abrupt and smooth transitions.
- The proposed method is implemented and verified by experiment tests.

ARTICLE INFO

Article history:
Available online 30 October 2014

Keywords:
Gait
Activity recognition
Wearable computing
Multivariate regression

ABSTRACT

The analysis and monitoring of the human daily living activities plays an important role for rehabilitation goals, fall prevention rehabilitation and general health-care treatments. Among these activities, walking is the most important daily motion. Studying the evolution of the gait cycle through the analysis of the human center of force is beneficial to predict any abnormal walking pattern. The analysis is based on the use of pressure-based mapping system that collects pressure and force measurement during the gait cycle. This paper deals mainly with the detection of the main characteristics of the gait phases. To this end, a segmentation of the center of force of the human body measure through the in-shoe pressure mapping system is performed to identify the gait phases. The proposed segmentation approach consists in modeling each segment by a regression model and using logistic functions to model the transitions between segments. This flexible modeling through the logistic functions has the advantage of detecting abrupt and smooth transitions between segments.

1. Introduction

Nowadays, industrialized countries suffer from continuous decreasing of physical activity level at work and at home. This may have direct impact on some chronic diseases such as cardiovascular diseases and certain types of osteoporosis [1]. In order to ensure 1000 Kcal of energy expenditure per week, the minimum recommendation of the World Health Organization is 30 min of moderate-intensity physical activity per day [2] such as walking, shopping, gardening, cleaning, etc. However, 60% of the world's population fails to achieve this recommendation [2]. Recently, many researchers have shown increasing interests in the study of the physical activity monitoring, the assessment of the human's energy expenditure, mental load and stress during daily living activities [3]. In the modern society, people are surrounded by and interacting with a number of electronic and mechatronic devices. Such devices are designed and programmed to provide the best convenience and the most helpful information to humans according to various situations. The devices are being rapidly and continuously evolved such that they recognize the feeling,

* Corresponding author. Tel.: +33 1 41 80 73 18.
E-mail addresses: samer.mohammed@u-pec.fr (S. Mohammed), allou-badara.same@ifsttar.fr (A. Samé), latifa.oukhellou@ifsttar.fr (L. Oukhellou), kckong@sogang.ac.kr (K. Kong), weiguang.huo@univ-paris-est.fr (W. Huo), amirat@u-pec.fr (Y. Amirat).
1 Tel.: +33 1 81 66 87 71.
2 Tel.: +33 1 81 66 87 19.
3 Tel.: +82 2 705 4766.
4 Tel.: +33 1 41 80 73 18.

http://dx.doi.org/10.1016/j.robot.2014.10.012
0921-8890/© 2014 Elsevier B.V. All rights reserved.

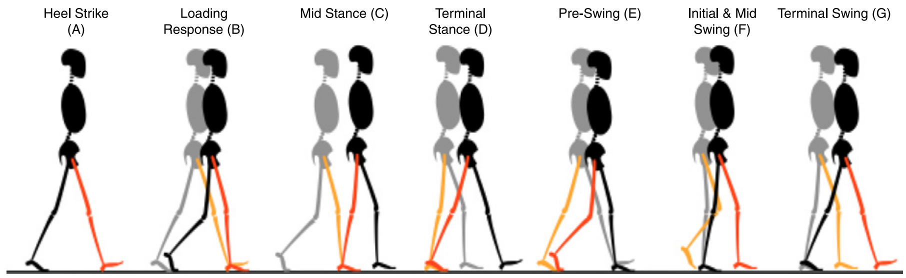

Fig. 1. Gait phases and their components.

emotion, and motion of the user for an autonomous and predictive response.

Recognizing daily human activities is fundamental to understand the human behavior, particularly, in a context of human assistive services. The last decades have shown increasing attention with regard to the non-intrusive monitoring tools for analyzing the everyday human activities. This fact may be related to the increase in the elderly's injuries due to falls [4] as well as due the continuous increase in the elderly population rate. Moreover, most elderly prefer to stay at home in the so-called aging in place [5]. The emergence of novel miniaturized technologies such as the wearable sensors is becoming a preferred solution for human assistive services such as remote monitoring, fall detection, security and well being. Recently, the use of such wearable sensors has considerably increased due to their evolution in terms of weight, size, energy consumption and cost [6,7]. Application fields are related to navigation, monitoring and artifacts control [8,9], human/robot localization [10,11], medical applications [12,13], etc. Wearable sensors can be flexibly used inside or behind objects without occlusion effects [14–16]. Environmental and object sensors such as smart phones, RFID, etc., are also used to quantify daily living activities [17]. Wearable sensors can also be attached to ankles to measure gait-related features during locomotion such as travel distance, velocity and energy expenditure [18,19].

Camera-based/optical motion systems used for human activity recognition are expensive systems, require a large space and high capacity of processing and image/video recordings storage and are limited to the laboratory conditions [20]. Moreover, these systems may interfere with person privacy. Recently, the Kinect camera-based sensor has been released by Microsoft for detection and recognition of human activities[6] [21]. The Kinect contains both RGB and Infra red (IR) cameras and offers several advantages such as low cost, depth information and ability to operate in the day as well as night. However the Kinect sensor suffers from limited field of view, occlusion problems in cluttered environment, dependence on surface texturing and poor performances in natural lighting [22]. Analyzing and monitoring the walking pattern of an elderly and impaired subject is beneficial for rehabilitation goals and fall prevention. Moreover, constraints related to the portability of the system as well as its ease of donning and doffing will enhance the acceptability of this new technologies by the frail and dependent people. In this paper we have studied the evolution of the gait cycle through the analysis of the human center of force. The analysis is based on the use of pressure-based mapping system that collect pressure and force measurement during gait cycles. The present study deals mainly with the detection of the main characteristics of the gait phases.

Among the techniques used in the literature for the human activity classification, one can cite those using supervised machine learning-based approaches such as K-nearest neighbor (K-NN) algorithm, the naive Bayes classifier and the support vector machines (SVM) [23,24]. A gait phase detection system for gait analysis is described in [25]. The system was designed to detect in real-time the stance, heel-off, swing, and heel-strike during a gait cycle. A gyroscope is used to measure the angular velocity of the foot and three force sensitive resistors were also used at the foot level to assess the forces exerted by the user on the ground. The gait phase detection is based on the use of a rule-based detection algorithm. A wearable system based on the use of an accelerometer at the waist level is proposed in [26] for real-time gait cycle parameter recognition such as cadence, step regularity, stride regularity and step symmetry. An autocorrelation procedure is used for that purpose. On the other hand, unsupervised-based approaches have also been used for human activity classification such as Gaussian mixture models (GMM) algorithms and hidden Markov model (HMM)-based algorithms. In this paper, the center of force of the human body is measured over time using in-shoe pressure mapping sensors and then segmented to the main sub-phases of the locomotion cycle. The measured data consist in multidimensional time series with several regime changes over time, each regime is associated with a subphase of the gait cycle. The problem of activity recognition can therefore be reformulated as the one of a joint segmentation of multidimensional time series; each segment is associated with a gait subphase.

The rest of the paper is organized as follows: Section 2 presents the gait walking pattern description and the data collection procedure. Section 3 shows the proposed multivariate regression model with latent segmentation. Section 4 presents the performances of the proposed approach in terms of gait sub-phases segmentation performance and Section 5 concludes the paper.

2. Gait walking patterns and data collection

Human walking involves repetitive patterns known as gait phases. The gait or locomotion cycle consists of two basic components, the stance phase and the swing phase. Each phase is associated with one limb and is composed as well of different sub-phases. As shown in Fig. 1, the stance phase consists of the following sub-phases: Heel Strike (A), Loading response (B), Midstance (C), Terminal Stance (D). The swing phase consists of the following sub-phases: Preswing (E), Initial and Mid-swing (F) and Terminal swing (G). This paper deals mainly with the detection of the main characteristics of the gait phases. The algorithm used in this study provides segmentation of the trajectory of the center of force of the human body. The main phases that will be detected are shown as follows [27]:

- Initial contact: during the initial contact, the leg starts contacting the ground (Fig. 1) and the Ground Reaction Force (GRF) appears only at the heel level.
- Loading response: time period from immediately following initial contact to the lift of the contralateral extremity from the ground, during which weight shift occurs.
- Midstance: when both the forefoot and heel start contacting the ground, as shown in Fig. 1, the Mid-Stance phase starts.

[6] Microsoft Corp. Redmond WA. Kinect for Xbox 360.