BIOCYBERNETICS AND BIOMEDICAL ENGINEERING 37 (2017) 701–717

Available online at www.sciencedirect.com

ScienceDirect

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

Original Research Article

Human gait pattern changes detection system: A multimodal vision-based and novelty detection learning approach

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ARTICLE INFO

Article history:
Received 11 May 2017
Received in revised form
1 July 2017
Accepted 10 August 2017
Available online 14 September 2017

Keywords:
Gait analysis
Lower limbs rehabilitation
Robotic walker
Novelty detection

ABSTRACT

This paper proposes a novel gait rehabilitation analysis system, based on an innovative multimodal vision-based sensor setup, focused on detecting gait pattern changes over time. The proposed setup is based on inexpensive technologies, without compromising performance, and was designed to be deployed on walkers, which are a typical assistive aid used in gait rehabilitation. In the medical field the evaluation of a patient's rehabilitation progress is typically performed by a medical professional through subjective techniques based on the professional's visual perception and experience. In this context, we are proposing an automatic system to detect the progress of patients undergoing rehabilitation therapy. Our approach is able to perform novelty detection for gait pattern classification based on One-Class Support Vector Machines (OC-SVM). Using point-cloud and RGB-D data, we detect the lower limbs (waist, legs and feet) by using Weighted Kernel-Density Estimation and Weighted Least-Squares to segment the legs into several parts (thighs and shins), and by fitting 3D ellipsoids to model them. Feet are detected using *k*-means clustering and a Circular Hough Transform. A temporal analysis of the feet's depth is also performed to detect heel strike events. Spatiotemporal and kinematic features are extracted from the lower limbs' model and fed to a classifier based on the fusion of several OC-SVMs. Experiments with volunteers using the robotic walker platform ISR-AIWALKER, where the proposed system was deployed, revealed a lower limbs tracking accuracy of 3° and that our novelty detection approach successfully identified novel gait patterns, evidencing an overall 97.89% sensitivity.

1. Introduction

Recent studies indicate that western societies have been progressively getting older, leading to an increased demand of healthcare services [1]. By the year 2030, half of the population will be above 50 years of age. Considering this tendency, the World Health Organization (WHO) has recently released a report addressing the importance of promoting rehabilitation services accessible to everyone [2]. This is a crucial concern

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http://dx.doi.org/10.1016/j.bbe.2017.08.002

since with age comes a higher risk of suffering cardiovascular complications and a natural decay of neurological, muscular and osteoarticular functions. These factors implicate a decay in motor functions that typically lead to gait disorders.

To provide better quality of life for those that suffer from some form of gait disorder, either from accidents, natural aging, or diseases (like Parkinson's, multiple sclerosis, and other degenerative conditions), rehabilitation has provided an invaluable help, to preserve and improve motor functions. Rehabilitation, as defined by the WHO, is the use of all necessary means to reduce the impact of the debilitative condition in order to provide the individuals a complete integration. Rehabilitation of the lower limbs involves techniques that stimulate these limbs by demanding physical exercise. It is usually aided by the use of walkers, so that the patient can support the body weight and walk around safely.

A fundamental aspect of rehabilitation is the promotion and monitoring of progression. As such we contribute to this research field by proposing a novel gait rehabilitation analysis system, based on an innovative multimodal vision-based sensor setup, focused on detecting gait pattern changes over time. To fulfill this goal, we propose:

- A novel multimodal vision-based setup to capture and model the lower limbs;
- A new lower limb modeling method based on Weighted Kernel-Density Estimation and Weighted Least-Squares for waist and legs' parts segmentation followed by a 3D ellipsoid fitting to model each part;
- A gait cycle identification method based on a temporal analysis of the feet's depth to detect heel strike events, preceded by a *k*-means clustering and Circular Hough Transform for feet detection;
- A novelty detection approach for gait cycle classification based on One-Class Support Vector Machines.

The system is capable of providing healthcare professionals, not only a tracking recording system, but also an automatic gait pattern's evolution assessment tool, avoiding the need to have them analyzing the whole data recorded at each session to assess therapy progression. The system learns the patient's present gait pattern and performs novelty detection to determine if future observations of the user's gait pattern (through the gait cycle) correspond to the introduction of a new pattern. Over time, and considering a certain percentage of the occurrence of novelty, our system considers that there is a new gait pattern present, and is able to learn it again, to continuously monitor its evolution in the future. Here, when we mention gait pattern's progression or therapy progression, we refer to a change in the gait parameters modeled by our machine learning approach, which attributes a novelty score to the observations. The system identifies a change in the gait pattern, but does not qualify it in terms of positive or negative therapy evolution. This task is reserved to the healthcare professional. The system, designed to be placed on board a walking aid, also has the advantage of eliminating the need of a fixed multi camera room setup, making it capable to operate in any unstructured environment, like the patient's home, and avoids the use of uncomfortable wearable sensors.

Our motivation was derived from the analysis of the respective literature. In the rehabilitation field, healthcare professionals rely on several methods to measure and track the progress of a patient's therapy, as mentioned by Baker et al. [3]. The oldest and most common of those methods is based on the professional's visual perception, being a subjective process dependent on experience. This method can be used during the patient's therapy, or off-line by analyzing a previously recorded video. More sophisticated methods are available, relying on visual-tracking systems using markers and several fixed cameras. These are expensive systems that track several points of interest of the patient's body, and provide a graphical representation of those points' positions over time. [4]. This approach requires a considerable amount of experience to correctly place the markers. There is a well-established work performed by Sigal et al. [5], which led to a public dataset for gait analysis studies. They use a visual-tracking system with markers as ground truth, and multiple cameras for a multi-view perspective, to allow the development and testing of image-based tracking and pose estimation methodologies.

Newer approaches have been proposed using other technologies, like Muro-de-la-Herran et al. [6] summarized. The use of visual-systems like time-of-flight cameras [7] and stereoscopic vision [8] has been proposed for gait recognition in biometrics applications. On the other hand, structured-light cameras, have been used for full-body motion analysis, as in [9]. These technologies allow the replacement of the marker-based visual-tracking systems, offering less expensive solutions. Other approaches rely on the use of inertial sensors that the patient has to wear on the body. Each unit provides accelerations of the different body parts for a posterior 3D modeling [10]. This latter approach is not constrained to a specific space in a room, but implicates a certain degree of discomfort for the user.

As previously mentioned, rehabilitation of the lower limbs is typically accompanied by the use of walkers, as such we focused our work on a system that could be deployed on these mobility assistances, without causing any discomfort for the user. In the literature, some preliminary works can be found, specifically with robotic walkers. The proposed instrumented rollator walker of Wang et al. [11] estimates gait parameters, like gait cadence, walking speed and stride cycle based on the readings from encoders, a gyroscope and an accelerometer, fitted to the walker frame. Lim et al. [12] uses a depth camera on a robotic walker to perceive the user's lower parts of the legs, and provide assisted rehabilitation by projecting footsteps on the floor, where the user has to step. While in [13] an approach just for feet pose estimation is proposed, without any kind of quantitative or qualitative analysis.

All the previously mentioned works focused on the capturing and posture estimation of the human motion, but none provides any kind of automatic over time analysis of the user's gait pattern, or of the rehabilitation therapy. Looking into the literature, we could find some works suggesting the application of machine learning techniques to classify specific gait patterns. For instance, Mezghani et al. [14] developed an approach to discriminate between an asymptomatic gait and an osteoarthritis knee conditioned gait, based on the 3D ground reaction forces. Djuric-Jovicic et al. [15] proposed an automatic identification system to detect disturbances