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Evaluation of deep convolutional neural networks for detection of freezing of gait in Parkinson's disease patients

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ABSTRACT

Background and objective: Freezing of gait (FOG) is a symptom that manifests as an episodic inability to move. It happens typically in patients with advanced Parkinson's disease (PD), and it is a common cause of falls in PD patients. The management of FOG is extremely difficult due to its sudden and transient property.
Methods: In this study, we implemented a novel FOG detection system that was based on deep convolutional neural network (CNN). By taking data segments from 1-dimensional (1D) acceleration signals as its inputs, the proposed CNN-based approach can realize automatic feature learning and discrimination of FOG events from normal walking in a streamline manner. By this way, it can remove the need for extracting hand-crafted features and the time-consuming feature selection. The proposed method was tested on a dataset comprised of more than eight hours of recorded lab data from 10 PD patients that experience FOG in their daily life.
Results: The final system achieved more than 99% classification accuracy in a patient-dependent setting, and an average of 80.70% accuracy in the patient -independent setting. The time for classification of a 4 s data segment is only 3.6 ms without the acceleration of graphics processing unit (GPU).
Conclusions: These results indicate that the proposed CNN-based system can provide satisfactory effectivity and efficiency in detecting FOG gaits if used suitably and can be beneficial to realize an accurate monitoring and gait assistance during daily living and rehabilitation therapy.

1. Introduction

The freezing of gait (FOG) is defined asa "brief, episodic absence or marked reduction of forward progression of the feet despite the intention to walk" [1]. Typically, FOG episodes are brief (1–2 s) and are associated with a subjective feeling of 'the feet being glued to the ground' [2]. It has been reported that about 50% of all Parkinson's disease (PD) patients regularly manifests FOG symptoms [3]. FOG may be the most distressing symptom of PD, and it is a common cause of fall, interferes with daily activities, and significantly impairs quality of life [4]. Schaafsma et al. [5] have defined five subtypes of freezing: start hesitation, turn hesitation, hesitation in tight quarters, destination hesitation, and open space hesitation. Detection of FOG, especially in the community environment, is very important for the clinical management of FOG, such as the monitoring of disease progression, decision-making of the duration of L-dopa treatment [6,7], and evaluation of new targeted interventions [8].

However, due to the episodic and paroxysmal nature of FOG, it is an extremely difficult task to measure and manage the FOG events. Until nowadays, subjective measures relying on patients' or caregivers' responses and clinician-mediated questionnaires, such as Unified Parkinson's Disease Rating Scale (UPDRS), Activities of Daily Living (ADL) part 14 [9] and freezing of gait questionnaire (FOG-Q) [10], still predominate in both clinical and research settings. During the past decades, the rapid development of sensor technology and emergence of corresponding signal processing methods have opened a door for objective detection and quantitative evaluation of the FOG events. Depending on the analyzed signal, these computerized methods can be roughly categorized into two groups, that is, one group of methods that are based on physiological electrical signal and the other group that is based on gait information. More specifically, the first group tries to predict or detect FOG event by monitoring the change of physiological signal such as electroen-

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cephalography (EEG) [11] and electromyography (EMG) [12,13] prior to or during the occurrence of movement disturbances. For instance, it has been found that during FOG the total amount of EMG activity is reduced in the lower limb muscles, such as shin [12], the tibialis anterior (TA) and gastrocnemius (GS) [13] muscles. Such findings and several correlated studies [14,15] suggest that there is a relationship between FOG, specific deficits in cognition and impairment in the motor planning mechanism.

For the purpose of detecting or monitoring, it is more convenient and straightforward to analyze the gait signals, either kinematics [7,16–20] or kinetics [21,22]. The reason is self-evident since gait information reflects directly how the FOG activity behaves. For analyzing gait kinetics, Hausdorff et al. [22] measured plantar pressure by using the pressure sensitive insoles. They found that freezing was not random, uncorrelated attempts at overcoming motor blockade. Instead, the forces under the feet oscillate in a fairly organized pattern. As for the analysis of gait kinematics, currently available methods for FOG detection can be further grouped into three categories: a) 3-dimensional (3D) motion analysis using reflective markers [18]; b) plantar pressure measurement [19]; c) the utilization of inertial sensors such as accelerometers, gyroscopes or a combination of both them [7,16–18].

From the perspective of long-time monitoring, gait analysis based on wearable inertial sensors seems to be more attractive compared to the other methods due to its cheapness and low-power consumption. One representative benchmark was presented by Moore et al. [17]. In their work, the vertical acceleration signal of the left shank was collected and analyzed by using an ankle-mounted sensor array, and most importantly, they defined the power in the 'freeze' band (3–8 Hz) divided by the power in the 'locomotor' band (0.5–3 Hz) as a freeze index (FI), which has now become a 'gold standard' for assessing the severity of gait freezing. Afterward, several improvements [16,23] were further proposed to improve its accuracy and reduce the detecting latency. However, FI together with some other measures, such as cadency variation [24] and entropy of the acceleration signal [7], can only provide a linear classification capability. Therefore, to achieve better detecting performance, more sophisticated mathematical tools are needed to deal with high dimensional space spanned by more than one features. For this purpose, machine learning technique is an important tool and its applications to FOG detecting were also reported in several recent studies. Pepa et al. [24] developed a fuzzy rule-based system where freeze index, energy, cadency variation and the ratio of the derivative of the energy were used as the feature vector. Handojoseno et al. [11] extracted multiple features from EEG signal, such as subband wavelet energy and wavelet entropy, and then the back propagation neural network was utilized to implement the detection of FOG events. Tripoliti et al. [7] proposed a random-tree-based classification system where the feature vector was comprised of the entropy of the signals from accelerometers and gyroscopes.

Though some encouraging results have been achieved for the application of machine learning technique on FOG detection, different from image or video signal, it is hard to capture intrinsic properties embedded in various time series data due to the random onset and duration of a target event [25]. Furthermore, for biomedical signals, there exist some additional challenges. For example, each individual has a different baseline healthy state, and variations compared to their own baseline may just indicate whether they have deviated from their optimal health state [26]. Recently, deep learning (DL) technique and in particular convolutional neural networks (CNN) have obtained impressive success in many signal processing problems due to their strong modelling capabilities for different applications, such as speech recognition [27], object classification and detection in computer vision [28], and nonlinear regression [29]. For classification problem, the most appealing

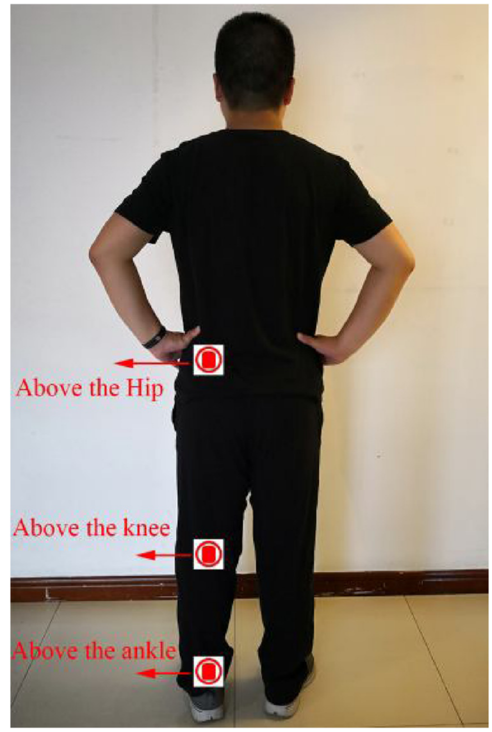

Fig. 1. Schematic view of the sensors placement.

property of CNN lies in two aspects: first, it can provide an end-to-end pipeline to realize the pattern classification; second, by using convolutional kernel with different size at different layer, the CNN can learn most fundamental features that are hard to be designed manually. Recently, inspired by the success of DL in computer vision, there has emerged a great interest in applying CNN to time series signals, such as human action recognition [30], electrocardiogram (ECG) signal classification [31], and fault diagnosis using vibrational signal [32]. The purpose of this study is to evaluate the classification performance of CNN-based approach for FOG detection. As far as we know, similar studies have been seldom reported in the past several years. With the encouraging results obtained in the experiments, we hope this study can provide an alternative way that is based on the newly emerging DL technique for an accurate detection of the FOG events by using wearable inertial sensors.

2. Methodologies

2.1. Description of dataset

The FOG dataset used in this study was contributed by Bachlin et al. [16]. It was built by using three different on-body accelerometers to collect the leg movement signals. The placement of the sensors on the patient's body is shown in Fig. 1. One sensor was located at the lower back, just above the hip of the patient. The other two sensors were installed on the patients' left leg: one was at the thigh, just above the knee, and the other at the shank, just above the ankle. Ten PD patients (7 males and 3 females) took part in the study. Age ranged from 59 to 75 years (mean ± standard deviation, SD: 66.4 ± 4.8 years), and Hoehn and Yahr (H&Y) score in ON period ranged from 2 to 4 (mean ± SD: 2.6 ± 0.65). Here, ON period referred to times when the medication was effective. According to the experimental protocol, the patients were asked to walk at their normal pace with three different tasks to simulate their daily activities for the purpose of provoking FOG event. The acceleration signals were sampled at a frequency of 64 Hz and transmitted to a