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Wearable sensors for gait pattern examination in glaucoma patients

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ABSTRACT

This paper presents a wearable wireless sensor system designed for real-time gait pattern analysis in glaucoma patients. Many clinical studies have reported that glaucoma patients experienced mobility issues such as walking slowly and bumping into obstacles frequently. The gait attributes of glaucoma patients, however, have not been studied in the literature. We design and develop a shoe-integrated sensing system for objective bio-information collection, utilize signal processing algorithms for feature estimation and leverage machine learning as well as statistical analysis approaches for gait pattern examination. The developed sensor platform is utilized in a randomized clinical trial conducted at UCLA Stein Eye Institute with 19 participants. Our trial involved both glaucoma patients and age-matched healthy participants performing a series of gait tests. With the captured sensor data, we develop signal processing and machine learning algorithms to provide a quantitative comparison between gait characteristics in older adults with and without glaucoma. Our results demonstrate that machine learning algorithms achieve an accuracy of over 80% in distinguishing extracted gait features of those with glaucoma from healthy individuals. Our results also demonstrate significant difference between two groups based on extracted gait features. In particular, several features are highly discriminative with a p-value of less than1×10^{-10}.

1. Introduction

Glaucoma is the second leading cause of blindness, and approximately 2% of adults over the age of 40 suffer from this condition [5–7]. The estimation shows that the prevalence of glaucoma in the world will increase to 79.6 million by 2020 [7]. Several different types of glaucoma exist with the most common type being Primary Open-Angle Glaucoma (POAG), which has been diagnosed in about one percent of Americans. Patients with POAG often are not aware of the medical condition until the symptoms have advanced significantly where the condition turns into a serious irreversible vision impairment [5].

Due to the high prevalence of glaucoma in older adults, there are numerous studies seeking to gain understanding of the effect of glaucoma on quality of life. A number of studies reported that glaucoma patients walk more slowly than non-glaucoma subjects [6], bump into objects more often, have increased postural sway [8], and they are prone to fall [9].

Logan et al. [4] have reported that vision plays multiple roles during locomotion, such as gait cycle modulation, navigation, and obstacle avoidance, which are reflected in the dynamics of trunk control. Moreover, a number of studies proved that vision has various effects on gait patterns [3,14]. Therefore, visual impairment has inevitable effects on individual's gait behavior. Although the relationship between glaucoma and quality of life has been established in many papers, there is still a lack of a quantitative gait analysis for glaucoma patients.

Gait analysis is the systematic study of human locomotion [1]. It has already been adopted in the diagnosis of physical impairments as well as monitoring the rehabilitation progress, since it can reflect one's mobility [[1], [2]]. A stable gait pattern depends on neuronal spinal and supra spinal pattern generators as well as sensory feedback from visual, vestibular, and proprioceptive systems. The system primarily responsible for dynamic stability in normal walking is the visual system [3].

Several studies reported on the kinematics of locomotion in case of low vision. Nakamura [14] compared step-time parameters of gait in normally sighted, late blind and blind from birth individuals. He concluded that blind individuals had a shorter stride length, slower walking speed, and a prolonged duration of stance. Another study [11] has performed biomedical analysis of gait patterns for young adults with and without visual impairment, and demonstrated specific differences between these two groups in uncluttered environment.

In this study, we collected quantitative gait information in real-time and carried out gait analysis for subjects with glaucoma

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disease. We established a series of gait experiments to observe specific gait patterns of two groups of individuals, namely healthy and glaucoma subjects, participating in our clinical study [32]. Participants were required to wear a custom-designed shoe-integrated motion sensor system during the gait experiments to acquire temporal and spatial gait measures.

We then extracted statistical features from automatically segmented sensor signals and trained several machine learning models with these features for the purpose of classification. Machine learning algorithms have already been adopted in the area of smart health as an assistive indicator in detection and diagnosis of many conditions [35]. Leveraging machine learning algorithms to identify glaucoma patients based on gait patterns offers an objective and practical method to automatically assess one's eye condition through simple tasks, such as normal walking, which can be carried out by non-specialist in daily life.

We further applied feature selection algorithm to identify predictable features, and performed statistical analysis over the selected features to further compare the difference in gait patterns between glaucoma patients and healthy controls.

The main contributions of this paper are (1) we design and develop an approach for glaucoma identification through gait analysis using wearable sensors, and evaluate its effectiveness via clinical experiments on glaucoma patients; (2) we demonstrate the potential of machine learning techniques to distinguish glaucoma patients from healthy controls according to their gait behaviors; (3) we perform statistical analysis to highlight highly discriminative gait features between people with and without glaucoma.

The rest of this paper is organized as follow. In Section 2, we discuss the related research studies in the area of wearable computing, mobility assessment and gait analysis. Section 3 introduces our system architecture and data analysis approaches. Section 4 covers clinical experimental design as well as participants' demographics. Section 5 presents and discusses the results of applying machine learning algorithms and statistical analysis on extracted features. Section 6 discusses the potential of our study and introduces our ongoing effort in the area of gait analysis for patients with visual impairment and the future research directions. Finally, we conclude our current study in Section 7.

2. Related work

Machine learning techniques have already been adopted in glaucoma type classification [21] as well as glaucoma detection at latter stage [22–24]. However, the studies regarding gait information in visually impaired individuals and particularly, in glaucoma patients are scarce.

To record gait information, early studies used clinician's observation, reflective markers and camera [11,12,14] or electric mat with pressure sensors [13]. Nakamura and colleagues [14] have placed reflective markers over eight distinct places on the body of visually impaired subjects during the 10-Meter-Walk experiment, and a motion analyzer system was used to record the trajectories of the markers. In another study [11], automated infrared camera and reflective markers were also used in a gait pattern analysis of 10 young adults with a visual impairment and 20 age-matched controls. The results demonstrated the difference between the young adults with and without vision impairment for locomotion control in uncluttered environment.

Even though these approaches could digitally record gait patterns precisely with low noise, they require a controlled laboratory environment and usually expensive to set up.

In light of the proliferation of wearable technologies and the development of various continuous monitoring body sensor networks, many studies adopted or explored sensor-based approaches for human movement monitoring, which can provide flexible and quantitative measurements of gait patterns.

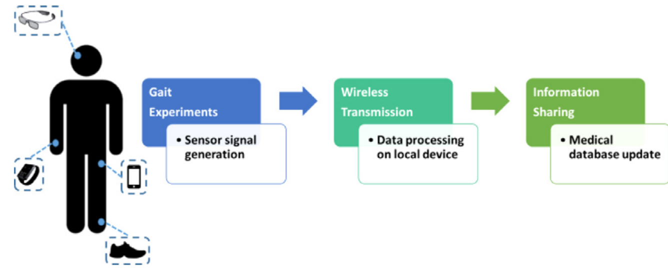

Fig. 1. Gait study using wearable sensing systems.

In one study [16], authors developed a sensor-based wearable device with integrated gait and balance analyzing algorithms, and conducted walking experiments on Alzheimer's disease patients to explore their gait patterns and postural sway characteristics. In another study [2], two accelerometers were used to measure the acceleration patterns of the head and pelvis during the walk for the elderly. Their results showed the difference in the movement of head, hip and leg during the walk, as well as variability in steps between older people who fell frequently and who did not. In [17], authors developed a smartphone application, which captures the subject's movements through built-in motion sensors, determines the time interval of a standard gait test and quantifies its individual phases. The test descriptors can be optionally uploaded into a medical database.

In addition to accelerometers and gyroscopes, many other types of wearable wireless sensors were involved in the studies for human movement analysis. Bamberg and etc. [18] introduced a shoe-integrated sensor system providing a quantitative gait analysis approach. Besides motion sensors, their system also included force sensors, bend sensors, dynamic pressure sensors, and electric field height sensors. Another study [19] utilized the signals generated from force sensing resistor and accelerometer during a 6-Meter-Walk experiment performed in a laboratory condition. The signals were taken as input and then trained a neural network classifier to determine the gait phases of stance and swing. In another study [20], the authors designed and developed a real-time gait phase detection system with three force sensitive resistors taped on the shoe insole, and one gyroscope attached to the posterior aspect of the shoe. Their experiment result demonstrated the system's high capability of gait phase detection with an accuracy of over 99%.

3. System architecture and data processing

Fig. 1 shows the general architecture of gait analysis using wearable sensing systems. The biophysical information is collected using various sensor-embedded equipment during gait experiments, then wirelessly transmitted to a local computer or smartphone for signal processing and data analysis, and the result is automatically sent to the physician for future examination, or uploaded to private medical database.

For this experimental study, we use shoe-based wearable system for motion monitoring and gait analysis. The signals collected using wireless sensors are transmitted, in real-time, to a local computer via Bluetooth. We then perform data analysis off-line. The following text in this section introduces our motion sensor platform and data analysis approach in detail.

3.1. Motion sensor platform

We designed a shoe-based wearable sensor platform for real-time gait monitoring, as shown in Fig. 2. This platform consists of a