Monitoring Neurological Disorders with AI-enabled Wearable Systems

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ABSTRACT

The age distribution has changed in Europe over the last decade. The group of 45 year-olds and above has increased and the median age in the EU is estimated to increase by 4.5 years during the next 3 decades reaching a median age of approximately 48.2 years according to Eurostat. A similar trend is noticeable in the United States, where the median age increased by 3.3 years from 2000 to 2020 according to Statista. Neurological diseases, such as Huntington disease, have a highly variable onset of 30 - 50 years but they are more prevalent to the older population. One of the first observable physical symptoms is chorea which includes random, uncontrollable and involuntary movements. Internet of Things and wearable systems can assist long-term monitoring of digital biomarkers such as plantar pressure and gait pattern which are associated with the aforementioned neurological disease. Emerging artificial intelligence models can be utilized to monitor the related digital biomarkers and check if these demonstrate a potential pattern denoting the presence or the development of a neurological disease. Enabling long-term monitoring by utilizing a unobtrusive wearable will increase the possibilities of early diagnosis, a longer life expectancy, and an improved quality of life for the patient.

CCS CONCEPTS

• Human-centered computing → Ubiquitous and mobile computing; **• Computer systems organization → Embedded and cyber-physical systems**; **• Applied computing → Health informatics**.

KEYWORDS

wearable systems, digital biomarkers, embedded mobile learning, smart health

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1 INTRODUCTION

Huntington disease (HD) is a progressive neurological disease that causes uncontrolled movements, psychological problems, and lack of cognition. HD has an onset spanning from 30 to 50 years but there is a higher probability to observe neurological disorders in the elderly population [26]. In the European Union (EU), the population is older than the United States (US) and even older than the rest of the global population. This is an emerging point to be taken into consideration: our societies are getting more prone to age-related neurological disorders [12]. For instance, in US the prevalence of HD in 2017 was calculated to be 13.1 per 100.000 persons [14], in Europe in 2011 this was estimate to be 7.5 per 100.000 persons [45], and in Denmark 5 − 8 per 100.000 persons [15]. Given that HD has a large genetic component, a common tactic from healthcare professionals is to monitor patients with predisposition to the disease (presymptomatic) and follow them as they eventually show signs of motor symptoms (i.e, symptomatic). This tactic requires clinical examination and also patients with lightweight symptoms might get a late diagnosis. For instance, during the early stage of HD, the first symptoms exhibited, half of the times are psychiatric and there is a significant probability of these not being identified [40]. Afterwards, motor symptoms such as chorea [40] (involuntarily and irregular muscle movements) appear. The patients which are diagnosed after the motor symptoms have emerged or when the motor symptoms become severe, are already in the middle or late stage of the disease. In this position paper we argue that a shoe wearable will be able to assist HD patients and potentially patients neurological diseases which exhibit motor symptoms on the lower limbs. More specifically, using a wearable system which is able to monitor the associated digital biomarkers (i.e., gait impairment) will offer the potential for earlier diagnosis, facilitate more accurate monitoring of the development of the disease, evaluate more consistently the treatment response and consequently provide a better experience and increased life expectancy for the patient. In addition it will decrease the burden of clinical examinations and it will allow us to acquire the digital biomarkers in a large scale and generate dataset to investigate the variance of symptoms among the patients.

A wearable system able to monitor motor symptoms will be able to be utilized in other neurological diseases beside HD, like Parkinson Disease (PD), Multiple Sclerosis (MP) for example. The population in Europe and most of the western societies is following a trend which underlines an increasing median age [1, 44] and therefore an increasing prevalence towards neurological diseases [12, 26]. This development can pose several challenges to the socio-economic sector of a country. For instance, neurological disorders account for a large percentage of the global health burden [26]. Introducing a wearable system like the one mentioned above, beside improving the patients lives, it can also contribute to reduce the burden from the healthcare systems which are having a hard time to serve an increasing amount of patients already.

Digital biomarkers can be described as vital physiological or behavioral parameters which are quantifiable, objective and can be measured through digital means such as sensors. The combination of Internet of Things (IoT) and Artificial Intelligence (AI) are used in several application scenarios, such as in activity monitoring [29], where the sensed data can identify a specific activity with the aid of embedded AI [18]. IoT and AI can assist in monitoring statistics in sports technologies and support training sessions to improve specific techniques [33, 47]. In health and safety, a shoe wearable in combination with emerging long-range wireless technologies, can serve as an emergency system [36]. The use case domain of IoT combined with AI is getting wider, including applications such as smart agriculture [16], industry 4.0 [31], and healthcare [42]. In addition, Wearable systems are used to self-monitor chronic illnesses, for example diabetes [3], or monitor fall detection in the elderly [46]. These new technologies have enabled personalized long-term monitoring through wearables [4, 5, 19, 27], which offer multiple benefits, including the self-evaluation of the individual's health goals, the explanation of implicit behaviors as well as early detection and prevention of diseases.

We envision a computational framework that is able to assist HD patients which is composed by emerging technologies such as IoT, embedded AI, wearable systems, and Low Power Wide Area Networks (LPWANs) [39]. More specifically, we introduce a shoe-based wearable system, which will obtain digital biomarkers related to HD and use them as input to AI models. The wearable system implementation will be based on low-cost commodity electronics and powered through a combination of battery and energy harvesting means [34]. Our hypothesis is that an unobtrusive, low cost wearable may be used to follow the disease progression of HD and detect it during the early stages, with the assistance of AI models. Moreover, it could be used to evaluate the treatment response on motoric function. Figure 1 illustrates the operational framework of the proposed wearable system which functions as a closed-loop feedback . A wearable should be distributed to patients with disposition to neurological diseases, within the onset domain of the specific disease. The wearable system will be performing a long term monitoring of the motor symptoms, utilizing the digital biomarkers through low cost sensors and consulting the pre-trained AI that is executed on the device. If the AI will detect an alarming pattern it will contact the healthcare professionals to propose a treatment to the patient. Then, the treatment response will be evaluated through the same loop.

2 NEUROLOGICAL DISEASE MONITORING

Uncontrollable temporal gait and high variance in temporal and spatial measurements is observed in symptomatic HD, however these symptoms usually start in the presymptomatic state in a lighter form that requires clinical and neurological examination to be identified [38]. Gordon et al. [17], quantified arm chorea effect using smartwatches and smartphones based on 10 HD patients. The wearable systems have the potential to capture such movement disorders but additional data are needed since the pattern of the movement disorder varies from patient to patient. A tri-axial accelerometer sensor was placed to the upper sternum on presymptomatic and symptomatic HD subjects to detect balance and gait impairments. The sensor data were compared with a computerized walkaway and the results were converging in a high degree [11]. Parkinson disease (PD) and HD subjects participated in a study where 5 wearables were deployed on the chest and upper limbs to monitor activity and to evaluate the user experience [2]. After two days of use at home 86% of the participants were positive or very positive to continuing wearing the sensors. An insole wearable which is able to capture gait pattern by using low-cost force sensors is described in [22]. The wearable was able to distinguish abnormal gait patterns by hemiplegic stroke subjects with a decent accuracy depending the movement disorder. A different approach, which is monitoring the gait pattern based on a wearable utilizing ultra-wideband (UWB) radio is illustrated in [6]. The results of this compared with the clinical gold-standard GAITRite.

The Unified Huntington's Disease Rating Scale (UHDRS) is the standard metric for motor impairment in HD but it is subjective and limited to in-clinic assessments. An unobtrusive wearable system based on a regular shoe which in combination with an LPWAN, an emerging wireless technology in IoT which can achieve long range communication at a low cost [32], can be completely seamless in environments such as smart cities. With the support of AI the technology will be able to identify lower limb movement disorders, including chorea, with high accuracy and without clinical and neurological examination in a low-cost and long-term manner.

3 SYSTEM OVERVIEW

The system we propose is oriented around several emerging technologies. This section motivates the selection of these technologies and provides a brief technical overview of each one.

The wearable system itself will be based on a regular shoe such as the one depicted in Figure 2, which depicts the design of a shoe wearable designed for obtaining the plantar pressure and the accelerometer sensor readings for biometric purposes [41]. Of importance, the wearable should be unobtrusive to provide the similar user experience as a regular shoe would. This should reduce the risk of user bias due to their digital biomarkers being monitored and the user will be able to walk and perform all their daily activities as they would normally. We decided to use a shoe wearable because it is a footwear that everybody uses everyday. Therefore, it is impossible to forget it or notice it, in contrast with a wristband or a neck wearable. Considering that a large part of the audience

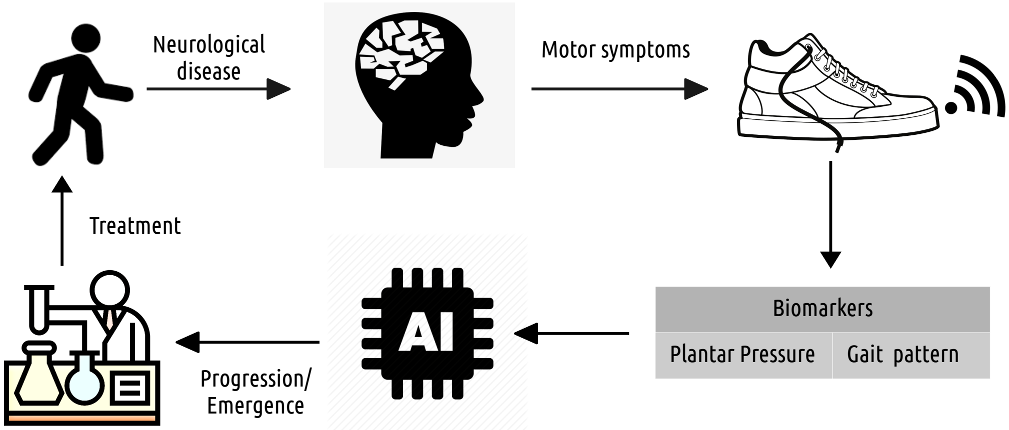


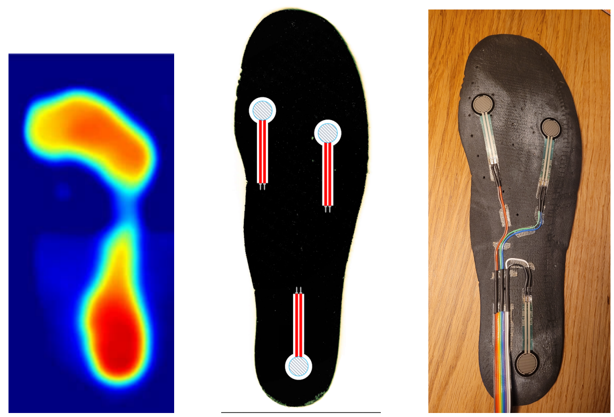
Figure 1: The computational framework to assist patients with neurological disorders. The framework functions as a close-loop feedback starting from the patient then the wearable obtains the digital biomarkers and uses them as an input to the pre-trained AI which runs onboard. Then the AI contacts the healthcare professionals in case of an alarming pattern occurs and they propose a treatment to the patient. Finally, the treatment response is evaluated as well using the same digital biomarkers.

Figure 2: Shoe wearable designed for acquiring the plantar pressure and the accelerometer sensor readings for biometric purposes [41].

we target is elderly, the likelihood of forgetting to use an additional wearable is higher.

In order to obtain the desired biomarkers we plan to use force sensors as examplified in Figure 3, where three force sensors are used to capture the plantar pressure for biometric purposes. Force sensors are cheap and very efficient at capturing the plantar pressure. This in combination with an accelerometer allows capturing of the gait pattern. The sensor energy consumption should be powered by a combination of battery and energy harvesting sources. Note that this is not a final design but a preliminary example. The amount of force sensors and their deployed position is a challenge which should be investigated further considering the tradeoff between the consumed power of the sensors and the accuracy of the digital biomarkers.

LPWANs are offering battery powered long-range communication for the IoT [30]. An LPWAN can be powered solely by a battery and have a lifetime of around 2 to 4 years approximately, depending the selected configuration [28]. LPWANs are also very tolerant to noisy environments where interference levels might be high [13, 35]. LPWANs are utilized mostly in smart city applications,



(a) Heat map of plantar pressure [24] **(b) Drafted sole layout** **(c) Implemented sole layout**

Figure 3: Chosen sole layout for force sensors used to capture plantar pressure for biometric purposes [41].

such as distributing energy based on people demands [9], smart parking models which predict available free positions based on previous data and many more have emerged to improve daily life [25]. LPWANs are not limited to applications around smart cities and there are examples of cases around activity monitoring and health [21, 37]. The authors in that case highlight that the high robustness and the long-range connectivity can have an impact in activity monitoring and health scenarios compared with the typical wireless technologies (Bluetooth Low Energy, IEEE 802.15.4). Considering the proposed computational framework, the long-range connectivity is of high importance to design a seamless wearable. This, because in an environment where there are an adequate amount of gateways (i.e., smart city) the wearable system can operate more "independently" without the requirement of a smartphone or short-range gateway.

The usage of AI for IoT has some drawbacks. Since the IoT devices have constrained resources (i.e., memory, computing, energy) the raw data have to be transmitted to a cloud server, where the AI typically processes the data. A cost is introduced because of the communication itself and it is known that the radio component is the one that consumes the most power in an IoT device. Then there is a throughput limitation based on the used communication technology (BLE, WiFi, LPWAN). Another issue which is very relevant to the focused use case is that if the the application scenario utilizes personal data, location, or digital biomarkers, such as heart-rate and number of steps, there are privacy concerns if these data are transmitted directly to a cloud and not stored within the device. Users would feel less concerned if they were ensured that their data would be kept inside their device/wearable. Less than 1% of the data generated from IoT devices are used today, due to the mentioned reasons [10, 20]. Hence, tackling the aforementioned issues would allow us to use more of the generated data and deliver more efficient AI models. One way to tackle these issues is to conduct the AI onboard, on the edge device, of course that would include other challenges, for example: less resources to execute the AI models, limited memory to store the data and less energy if the device is battery powered. The research and industry community is attempting to overcome the above challenges through several paradigms. For instance low power hardware accelerators are designed [23] and software libraries [7] are developed specifically to support AI for IoT applications. TinyML [43] is a foundation including hardware, algorithms and software designed for microcontrollers designed to operated at ultra low power, typically in the mW range and below.

3.1 Our position

Our position is that we should integrate the proposed computational framework within the smart healthcare context since it will offer multiple benefits. One of the main issues of neurological disorders symptoms, and HD specifically, is that they may vary a lot between different patients. Using a low cost wearable will help to acquire long-term data from diagnosed patients from all states in a large scale, to generate a dataset including the associated digital biomarkers. Such a dataset will be a valuable asset for the research community which will help to investigate the variance and other useful statistics of the symptoms and enable more accurate and earlier diagnosis. Then, the dataset can be utilized to train the AI model which will run on the device to monitor the individuals with disposition for neurological diseases. The wearable with the assistance of the AI can be used to monitor and detect a concerning pattern which will notify the healthcare professionals and user. Furthermore, the wearable can be used to evaluate the outcome of neurological surgery. For instance, after hydrocephalus surgery the patient has to walk for a specific distance and the doctors have to evaluate empirically the motor movements of the patient, this to assess if the surgery was successful or not [8]. A wearable system would allow monitoring of motor movements and associated biomarkers over an extended time period following surgery, hence potentially improving the assessment.

4 CONCLUSIONS

In this position paper, we have proposed a framework that is able to assist HD patients and potentially other neurological disorders based on a shoe-based wearable system. The framework is comprised by a combination of technologies namely, wearable systems, IoT, embedded AI, LPWAN operating in an environment where there are sufficient amount of LPWAN gateways to offer connectivity. Modern societies are prone to an increasing healthcare burden due to age-related illnesses, such as neurological disorders. The proposed framework has the potential to offer an earlier diagnosis of the neurological disease, monitor the progression of the disease more accurately but also evaluate the treatment response on motoric function. Therefore, it will potentially improve the quality of life and life expectancy of the diagnosed patient. Furthermore, the technology will allow us to acquire the associated biomarkers on a larger scale and investigate the variance in symptoms (which is a current issue in this research field). Finally, the burden of the healthcare systems is expected to be reduced as the proposed framework will allow self-monitoring and the interactions with the healthcare professionals will be reduced to the cases of potentially alarming situations.

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