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Development of an Embedded Device for Quantifying and Recording Daily Standing Profiles in Individuals with Lower Limb Motor Impairment Using an Assistive Standing Mobile Device †

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Abstract: The present study introduces an innovative device designed to objectively record and quantify the daily standing profiles of individuals with lower limb motor impairment. The device is specifically developed to be seamlessly embedded onto the standing platform of an assistive standing mobile device, without compromising its structural integrity or functional capabilities. The primary objective of this device is to provide objective evidence of patients' standing activities within their home environment, thus facilitating the assessment of patient performance and usage. The embedded device captures and stores comprehensive data regarding the duration, frequency, and interval of patients' standing sessions. Furthermore, the device integrates wireless connectivity to facilitate data transfer and analysis. The development process involved close collaboration between rehabilitation engineers and physiotherapists to ensure optimal functionality, user-friendliness, and unobtrusiveness. Extensive testing and validation procedures were conducted to assess the reliability, validity, and feasibility of the device. Results demonstrate its high accuracy and reliability in capturing and quantifying standing profiles. The proposed device addresses a critical need within the field of rehabilitation, providing clinicians, researchers, and funding organizations with objective evidence of patients' standing abilities and adherence to rehabilitation protocols. This evidence-based approach has the potential to enhance clinical decision-making, improve treatment outcomes, and secure financial support for patients in need of assistive standing mobile devices. In conclusion, the embedded device presented in this study offers a novel and practical solution for quantifying and recording the daily standing profiles of individuals with lower limb motor impairment. By providing objective evidence of patients' standing activities, this device has the potential to advance the field of rehabilitation and facilitate improved access to assistive standing mobile devices for those in need.

Keywords: tele-monitoring; rehabilitation; standing training; patient compliance

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1. Introduction

1.1. Background

Lower Limb Motor Impairment is one type of disability in which individuals lose part of or whole ability of coordination of lower limb caused by stroke, spinal cord injuries or cerebral palsy. Patients experiencing this medical condition have to deal with difficulty in standing and walking. In scope of motor training of lower limb, robotic lower limb exoskeletons are commonly adopted in rehabilitation clinics for user-driven or passive gait training to enhance proper gait patterns, especially on young patients [1]. For senior adults and patients with upper body weakness, exoskeletons are not applicable due to their difficulties of maintaining body balance in upright posture. Although those patients are prohibited from walking due to restriction of operating lower limb exoskeletons, standing training are physiologically beneficial to, including but not limited to, reduce risk of pressure sore, improve gastrointestinal function and strengthen bone density [2]. To help patients performing standing training, numerous standing training aids have been launched to market such as standing frames and assistive standing mobile devices, a robotic device assisting patients performing standing and sitting.

Traditional facility-based rehabilitation models provide important clinical supervision but can be resource-intensive [3]. Accordingly, community-based rehabilitation has emerged as a cost-effective alternative to promote patient independence and functional recovery in real-world environments [4]. Recent study showed that home-based rehabilitation can effectively enhance functional and emotional recovery of various disabilities, including stroke and spinal cord injuries [5–7]. Well-planned remote rehabilitation programs become acceptable by patients to reduce their time on traffic and follow-up consultation, especially after the epidemic period. Therefore, home-based rehabilitation is not only beneficial to patients, but also treated as an alternative to traditional clinic-based therapies due to ease of cost in time, manpower and capital.

However, home-based rehabilitation is not meant to be a let-go policy, and delivering rehabilitation programs remotely presents challenges in objectively monitoring patient compliance. According to the National Library of Medicine, about 40% of patients failed to follow the medical advice, including prescribed treatments [8]. To be a responsible healthcare service provider, the procedure and progress of rehabilitation programs are required to be monitored in order to understand the situation of patients. Phone interviews and home visits are currently the most common methods to monitor the progress of recovery. Patients may fail to accurately report the participation of training by lying, false memory or memory loss. The progress of the rehabilitation programs is hindered, which possibly causes deterioration of lower limb ability and development of physiological disorders such as osteoporosis or kidney malfunction in future.

Therefore, in this study, we propose the implementation of a Standing Tracking system to tele-monitor the rehabilitation progress of patients who are prescribed standing training programs with assistive standing mobile devices. An additional embedded device was developed to record the time spent in standing training, and then upload standing data to a cloud spreadsheet. To facilitate the upload process, 4G mobile data communication module is integrated to the system allowing data transfer in residential and community environments. When patients step on the platform of assistive standing device, the Standing Tracking system would be started.

1.2. Related Work

There is a lack of specific research on the development of compliance monitoring about standing tasks with assistive standing devices. However, previous review studies have emphasized the major considerations about development and application of IoT service in rehabilitation [9]. Researchers proposed that, in terms of system design, the ease of system should be first considered since the tracking system is aimed to provide timely feedback to patients [10]. Meanwhile, the system should be compatible with problems to be solved and patients with different proficiency in technology, in order to avoid overuse of technology.

Devices and equipment were also recommended to be considered according to the system design, including the device for collecting, processing and sharing data and information. Communication protocol was required to be considered according to range of data transmission [11]. Besides, understanding the methodology of the rehabilitation program was needed to develop an appropriate IoT system, in order to promote significant system usability [12]. Studies also proposed that sensors shall be included in IoT systems to capture the movement of patients. However, sensors shall give minimum influence on patients' action. Sensors are expected to be ignored by patients even if sensors are detecting the activities of rehabilitation training [9].

2. Method and Material

The Standing Tracking system consists of 4 main components, including Microcontroller Unit, 4G module, Inertia Measuring Unit (IMU) and foot switch module. When patient's weight is applied to the foot switch, the microcontroller would be powered up, as well as the 4G module and IMU. The 4G module starts initialization to connect the 4G mobile data network. while IMU is initialized to acquire tilting angle. Then, the tilting angles data is uploaded to a cloud-based spreadsheet and available to be reviewed by therapists.

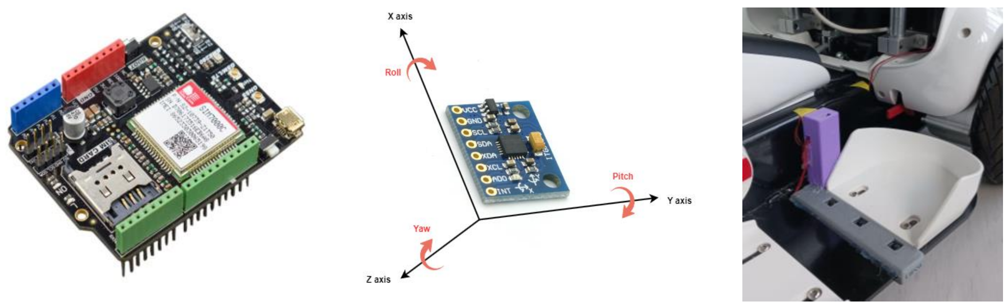
2.1. Components

2.1.1. Microcontroller Unit

In the tracking system, Arduino Mega 2560 (Arduino, Italy) is used as a microcontroller unit which distributes power to, initializes and communicates with peripheral devices. The embedded microprocessor is ATmega2560 (Microchip Technology, Chandler, AZ, USA), which can operate with 16 MHz in maximum clock speed. The microprocessor also includes 8 KB of RAM allowing process of 2000 floating-point numbers per operation, which suits for acquiring 3-axis of acceleration measurements from IMU. Lithium rechargeable battery module is used as a power source for supplying the Microcontroller unit. Program for data acquisition and transmission is flashed in the Microcontroller unit for operation.

2.1.2. 4G Module

4G module is required to establish the connection between cloud service and local data acquisition device. SIM7000C NB-IOT shield (DFROBOT) is used in the tracking system because it is compatible with the frequency band used for telecommunication in Asia region, and compatible with the Microcontroller unit for data flow and operation. Hayes AT command set (AT command) is the major command language for operation, which can be sent by Microcontroller unit through Universal Asynchronous Receiver/Transmitter (UART) protocol. Meanwhile, a SIM Card with registered 4G mobile data service is required for activating the module.



(**a**) (**b**) (**c**)

Figure 1. 4G module (**a**), Inertia Measuring Unit (IMU) module used in the Tracking Device (**b**), and Foot Switch module (**c**) of the proposed Standing Tracking Device.

2.1.3. Inertia Measuring Unit (IMU)

Besides standing training, general assistive standing mobile devices offer sitting assistance to patients to avoid exhaustion. Therefore, the tilting angle of the upper body arm is a necessary indicator of standing. In the Tracking System, GY-521 6-axis IMU is included for tilting angle measurement. Tilting angle is derived from measured 3-axis translational acceleration values. In terms of geometry, the tilting angle is described by pitch angle, which is defined as the angle between the *Z*-axis and axis of gravity. The conversion of pitch angle and linear acceleration is

$$Pitch\ angle = tan^{-1}\frac{\sqrt{A_x^2 + A_y^2}}{A_z} \quad (1)$$

(**a**) (**b**)

Figure 2. IMU integrated in Assistive Standing Mobile Device to measure the angle of the supporting arm. The device offers sitting mode (**a**) and standing mode (**b**).

The conversion is only valid if gravity is the only acceleration exerted on the IMU. Since standing mobile devices are prescribed for standing training only, angle calculation during driving, vibration or collisions will be neglected.

2.1.4. Foot Switch Module

Foot switch module, installed near the standing platform, is used to trigger the Tracking device. The module consists of 2 ends, which are connected to the power source and power input pin of Arduino Mega 2560 respectively. When patients are shifted to standing mobile devices, patients' weight is applied on the foot switch module, and the Arduino Mega 2560 is powered on. For effectively capturing the applied weight, the foot switch module includes an array of mechanical switches which are connected in parallel. When either one or more switches are pressed, the tracking device would be powered on.

2.1.5. Power Module

To power up the Tracking Device, 2 parallel connected 18,650 Lithium rechargeable batteries (2400 mAh at 3.7V in total) are used as source of power. A DC-DC transformer is installed to step up the supply voltage to 9V for input of the Microcontroller unit and 4G module. The device consumes 9V 100mA in data acquisition and processing period (80% time of cycle in average), while it consumes 9V 140mA during sending HTTP requests by 4G module (20% time of cycle in average). Battery discharging test has been conducted, and it is observed that 6 h of continuous usage is supported by the power module. For convenience of patients and caregivers, the battery module is charged by 5V DC power supply, which is common in domestic chargers for smartphones.

2.2. Mechanism

To start the standing training, patient steps on the standing platform as well as the foot switch module. The battery module then powers on the Microcontroller unit and 4G module. The Microcontroller unit sends AT commands to the 4G module to search and register the mobile data station according to mobile data service provider.

Meanwhile, the IMU is initiated for continuously acquiring the 3 axis of acceleration data, and computes the pitch angle according to formula (1). The Microcontroller unit then commands the 4G module to make HTTP POST request, which includes pitch angle data in form of JSON structure, and send to webhook. Once the request is received, the webhook can automatically relay the data and additional timestamp to the cloud spreadsheet. By using this network pathway, all data will be directly streamed to cloud spreadsheet, and no local data storage is included in the system. Since all the configurations are done before intervention, no extra settings are required after installation and distribution of Tracking Device.

Figure 3. Mechanism of the proposed Standing Tracking Device.

2.3. Data Validation

Data validation is crucial in tele-monitoring system since it serves as an indicator of data corruption. It is expected that the value of IMU measurement is in range of 0–90°, which is the range of movement of the upper body arm of the Assistive Standing Mobile Device. Therefore, any values out of this range or null values would be considered as invalid data. As the result, corrective maintenance would be conducted once null values are received in order to reduce the disturbance of the rehabilitation program.

3. Conclusions and Discussion

The main contribution of this study is the development of a standing tracking system integrated with assistive standing mobile devices and establishment of connection between the system and cloud spreadsheet. The proposed system adopts the idea of Internet-of-Thing (IoT), providing tele-monitoring function of device utilization and compliance of patients with prescribed home-based rehabilitation training. The system provides objective data for healthcare professionals to understand the progress of rehabilitation programs, and instant feedback can also be provided to patients as encouragement. Besides, there are no extra operation requirements for the Tracking Device except recharging the battery module, which suits patients with different levels of proficiency in technology and reduces the risk of operation failure. The ultimate goal of this research is to enhance the connection among the assistive rehabilitation devices and internet, adapting IoT on medical devices to promote tele-healthcare and rehabilitation near residential communities.

3.1. Compliance of Prescribed Intervention

An effective rehabilitation program requires cooperation between patients and healthcare professionals. On one hand healthcare professionals have to provide adequate instruction and feedback to patients, while on the other hand patients have to follow those instructions and perform corresponding exercises. By installing the Tracking Device system, the usage will be comprehensively uploaded to the cloud spreadsheet, which can significantly improve the efficiency of data collection and eliminate human error during progress evaluation. With accurately collected data, more appropriate interventions can be provided to patients.

3.2. Privacy

Privacy is the major concern by patients or caregivers when adopting tele-monitoring system. To solve this conflict, clinical professions shall regularly share the standing records to patients and caregivers accordingly. Therapists can illustrate the progress and improvement by acquired data to patients as positive feedback, which can pin a virtual target on patients psychologically. It is important to note that patient data will not be streamed to the cloud. Only standing profile information, such as duration and standing angle, will be accessible on the cloud. To maintain confidentiality, each patient will be assigned a unique code, allowing us to match their demographic information at the backend.

3.3. Accessibility

The intended users of the device are individuals with lower limb motor impairment who are participating in rehabilitation training, particularly standing exercises prescribed by clinical professionals. This device serves as a tele-rehabilitation equipment capable of monitoring patient compliance and capturing their standing profile over a specified period.

4. Limitation and Future Development

The foot switch module is a binary sensation module which considers only whether patients are performing standing training with assistive standing mobile devices. To obtain a comprehensive profile of the standing rehabilitation program, the distribution of weight bearing is also a key feature for indicating the quality of standing training. Uneven distribution of weight causes unequal force acting on tissues due to gravity, which causes extra pain, deformity and contracture [4]. Therefore, the pressure sensor will be considered as an additional sensor in future improvement versions, which can provide a description of symmetry of weight bearing. Feedback about symmetric standing posture is available for patients in order to reduce the risk of injury and bone deformities.

Apart from additional pressure sensor, future work will also include recruiting patients with lower limb impairment to validate the standing tracker tele-monitoring system. Being major portion of lower limb impairment, stroke group will be the first stage of pilot study, and will expand to other groups such as spinal cord injury. In preparation for the upcoming pilot trial involving patients, a formal research study will be conducted. Ethical approval will be sought from the hospital ethics committee to ensure compliance.

Informed Consent Statement: The author affirms the work's originality and confirms that consent was obtained for the inclusion of the patient's photograph.

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