Development of a Wearable Exoskeleton for Active-Assist Knee Flexion-Extension

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Abstract: Lower-limb rehabilitation exoskeletons have arisen as effective instruments for aiding patients with mobility issues in their recovery process and addressing the difficulties encountered by physical therapists, such as staff shortages and the physically demanding nature of repetitive sessions. Nonetheless, research has also shown that patients frequently develop a reliance on the passive assistance provided by such devices, which may result in a decline in the yield that can be acquired from rehabilitation training sessions. With this, the study highlights the development of a wearable exoskeleton for active-assist knee flexion-extension that can be adaptable and work in conjunction with other existing rehabilitation devices for knee movement. This system provides emphasis on the principle of effort, which in return results in the objective of the study in detecting motion intention and angle change for a period of every 100 milliseconds. Based on the obtained values, a control signal with knee flexion or knee extension as output would be provided if and only if the developed exoskeleton detects motion intention from the user but no change in angle was produced – denoting that the user's strength may not be enough to perform the intended action. This ensures the active participation of patients in their physical therapy sessions. Allowing for a mechanical input rather than utilizing physiological signals revealed great potential in reducing the risk of acquiring noisy data. Experimental results show that the developed exoskeleton has achieved a classification accuracy of at least 90% for detecting changes in angle and motion intention.

1 INTRODUCTION

According to the Global Stroke Fact Sheet 2022 of the World Stroke Organization [1], stroke remains to be the leading cause of long-term disability worldwide and the second leading cause of death with a global incidence of more than 12.2 million annually while the overall prevalence of stroke was found to be over 101 million individuals. This led to an estimated loss of 0.66% of the global gross domestic product [2]. In addition, with the increase in the average life expectancy of humans, the elderly population is rapidly increasing, and this is known to be closely interrelated with the increasing incidence of long-term ailments and disabilities wherein according to the United Nations [3], over 46% of older people globally, those aged 60 years and over, are considered as persons with disabilities (PWDs).

To address physical and mobility impairments, physical rehabilitation and are recommended to patients to recover their balance and mobility, in combination with other treatments to trigger neuroplasticity [4]. An effective rehabilitation is a customized process that is tailored to the individual needs of a patient. Designing rehabilitation programs for learning or relearning a motor skill includes the following principles: 1) practice, 2) skill specificity, 3) feedback, 4) attention, and 5) interest. As such, existing methods of physical therapy, specifically traditional rehabilitation and robotic rehabilitation processes, are performed on patients to address and cover the principles for motor learning. Conventional physical therapy heavily involves intensive labor provided by physical therapists (PT) and physicians, which is expensive and inefficient [5], [6]. With robotic rehabilitation, a physical therapist can attend to more patients at a time, which maximizes the PT's efficiency and potentially lowers the rehabilitation costs per patient as robotic assistive devices aid in eliminating manual assistance provided by the PT while performing with better motion accuracy, allowing the PT to focus more on performance evaluation and analysis of the patient [5], [7].

According to the study of Taravati et al. [8], patients have the tendency to develop a dependency on passive movements, which can lead to a decrease in active, voluntary movements. Rehabilitation devices that assist patients in performing passive-assisted ROM exercises are found to be less effective than active exercises [9]. Nonetheless, they are both similarly efficacious in improving individuals' functional fitness [10].

The performance of prosthetics and orthotics devices highly relies on their control algorithms as they specify how the robot or device would carry out its tasks and how it would react to external factors that may be brought on by the environment or the subject. With this, the assistive control strategies developed to aid subjects with insufficient muscle contraction to produce the desired movement and help them trigger neuroplasticity, the ability of the brain to rewire itself and bring back the sensory and motor functions of patients [11].

Powered orthoses for rehabilitation are continuously being studied and researched as robotic rehabilitation is still considered to be an emerging technology in today's Industry 4.0. These devices generally aim to aid PTs as well as patients in maximizing their therapy sessions to achieve a maximized gain; furthermore, these often employ sensors to obtain data that would be utilized for feedback to the PT, ensuring that the PT has quantifiable data about the patient's performance.

Based on the different literature discussed above, there is extensive research on the application of force sensors, inertial sensors, and EMG sensors. Most studies show that effort plays an important role in physical rehabilitation, often applying force sensors, inertial sensors, and/or EMG sensors to the device to obtain this information. In addition to that, there are also few to no studies on the development of an exoskeleton that is capable of being integrated with another existing rehabilitation device; thus, this paper aims to contribute to the existing literature by incorporating mechanical sensors to detect physical movement and effort of the subject to minimize error and data noise while being able to provide a control signal to the rehabilitation device that is connected with the system and assist the subject once needed.

1.2 Limitations of Current Control Strategies for Robotic Rehabilitation Technologies

Several limitations and challenges associated with existing rehabilitation assistance approaches can be identified:

1) Counterbalancing assistance is highly beneficial in performing activities that require a greater level of ROM; nevertheless, having a mechanical counterpart is as important to ensure the safety of the patient.
2) Impedance-based assistance may lead to the patient's passiveness over the training session, just after the patient produces enough effort to trigger the robot's assistance.
3) Lastly, EMG is helpful in monitoring muscle activation, but it is highly sensitive to several external factors – leading to the need to calibrate for every patient and every training session.

While these control strategies display promising results in assisting physical therapists and patients in performing rehabilitation exercises, one of the important points to consider is the accuracy of movement pattern assessment of the patient and the engagement of patients in various activities beyond structured therapy sessions.

Paper Contribution. The study specifically intends to determine and accomplish the following: (1) to develop of a 1-DOF wearable exoskeleton for active-assist knee flexion-extension; (2) to be able to measure and motion intention and change in angle produced by the human subject with a classification accuracy of at least 90%; and (3) to provide control signal based on the parameters obtained from the subject.

2 MATERIALS AND METHODOLOGY

Devices targeting physical rehabilitation are generally based on traditional rehabilitation practices in which a PT must manually assist the patient in performing therapy exercises, depending on the type and level of assistance needed by the patient. Concurrently, the PT senses and is aware of the patient's response to the assistance provided. Applying this concept, as illustrated in Figure 1, peripherals allowing for input are attached to the user

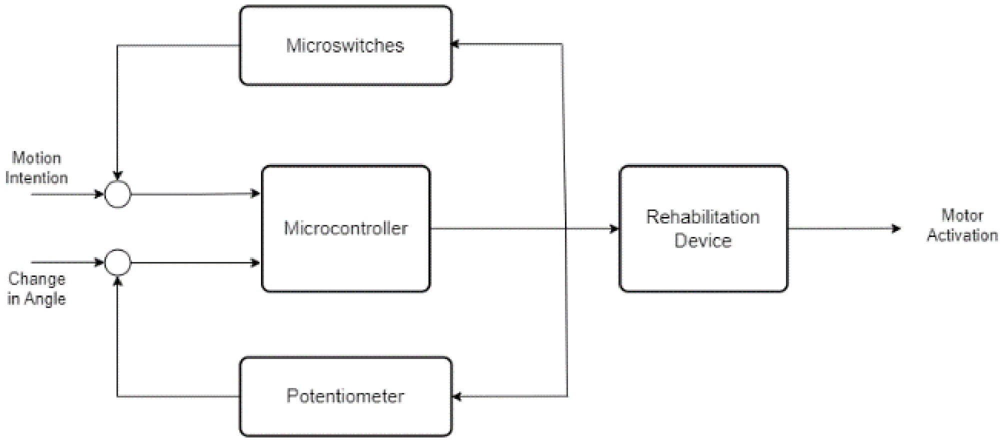


Figure 1: Control system for signal acquisition.

to determine his/her intention for movement and provide these feedback parameters to the microcontroller that is programmed with a control algorithm that would decide upon the response of the overall system – ensuring the patient's active participation throughout the therapy session.

Literally meaning the “outside skeleton”, an exoskeleton is an external frame that can be worn to support an animal’s body shape and works in conjunction with its user. This is typically made from rigid materials such as carbon fiber or fiberglass, but it can also be fabricated using soft and elastic materials such as wearable straps. For potentiometer placement, a simple linkage employing a revolute joint was applied. On the other hand, the device setup was simulated to be fabricated in actual using aluminium alloy 5083, as presented in Figure 2.

Figure 2: Developed exoskeleton with a human dummy.

2.1 Control Algorithm

In this study, a control signal would only be provided to the rehabilitation device to provide assistance if and only if the system has observed that the subject intends to move but has not produced an angle difference for a period of 100 milliseconds (ms). Shown in Table 1 is the truth table for the developed system.

Table 1: Truth table for the developed Wearable Exoskeleton.

Motion Intention	Angle Change	Control Signal for Motor Actuation
0	0	0
0	1	0
1	0	1
1	1	0

2.1.1 Arduino UNO

This microcontroller is used to monitor if the subject exerts physical effort and assist when the need arises to foster motor recovery. A control signal would only be provided to the rehabilitation device to provide assistance if and only if the system has observed that the subject intends to move but has not produced an angle difference for a period of 100 milliseconds (ms).

2.1.2 Normally-Open Micro Limit Switches SS-01GLP SPDT

Two microswitches are utilized to ensure that effort is given to perform the intended action – serving as the effort monitoring system of the study that aims to detect motion intention that could not be recorded by the change in angle (potentiometer). One microswitch is positioned at the anterior shank to measure the effort exerted by the subject during knee extension. In contrast, another microswitch is placed at the posterior compartment of the leg, also referred to as the calf, to detect efforts or motion intention in performing the knee flexion.

2.1.3 B10K Rotary Potentiometer

To ensure that the intended motion exerted by the subject is sufficient to be translated into movement, a B10K rotary potentiometer that has a resistance of 10K ohms, also known as the rotary angle sensor, is implemented as redundancy to increase the reliability of the system, which acts as the verification step of the process, before physical assistance is generated by the rehabilitation device connected to the system that would assist the subject in performing the action. In conventional PT practice or any physical activity, human movement is analysed based on visual observation [12].

2.2 Signal Acquisition

Both the motion intention and the angle difference are measured at a regular time interval. To determine the threshold value and the potentiometer's sensitivity, initial testing of the developed system was performed wherein the subject was at rest with the subject's leg at a 90-degree angle (with foot flat on the ground). Sampled at 100ms intervals, an experiment that lasted for 10 seconds long was conducted, resulting in a total of 100 samples. The absolute values of the recorded data were obtained for this experiment, as shown in Figure 3.

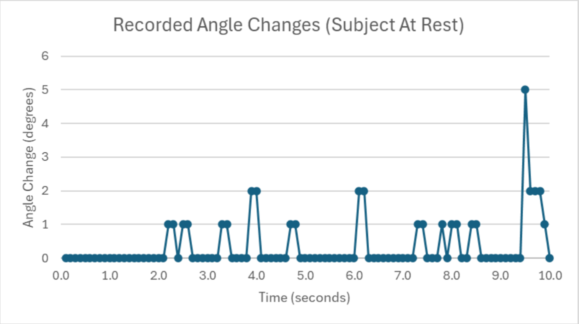


Figure 3: Recorded angle changes for potentiometer threshold (Subject at Rest).

It can be observed from the figure above that the potentiometer often plays its angular reading from 0 to 2 degrees (with an outlier of 5 degrees), even without the human subject producing any movement. As such, the threshold value for the variable resistor was set to +/- 2 degrees. At the same time, two normally-open micro limit switches SS-01GLP SPDT (single-pole-double-throw relay) are utilized to ensure that effort is given to perform the intended action – serving as the effort monitoring system of the study that aims to detect motion intention that could not be recorded by the change in angle (potentiometer).

2.3 Target Exercises

The subject was guided to perform the assigned exercise. In this study, knee flexion and extension were the specific tasks to test the developed exoskeleton. For knee extension, the subject was asked to sit upright with their thigh supported in a chair and with the left knee starting from a 90-degree angle and then stretch the leg out as far as possible, having about an angle of 180 degrees from a human's thigh and calf or is parallel to the ground. On the other hand, especially for powered and stationary rehabilitation exoskeletons that consist of actuators, similar to the TAYÔ prototype of the Institute of Biomedical Engineering and Health Technologies (IBEHT), the knee flexion refers to the movement of bringing the calf back down to the ground, having about an angle of 90 degrees, also measuring between the thigh and calf. These exercises aim to help strengthen the thigh muscles and regain the knee's range of motion. Figure 4 represents the knee flexion-extension exercise.

Figure 4: Knee flexion-extension [13].

3 RESULTS AND DISCUSSION

This chapter presents relevant data and results gathered from this study. A total of 30 trials were performed to determine the classification accuracy of the developed system, in which its data were recorded at a sampling rate of 100 milliseconds. Material Comparison.

3.1 Developed Exoskeleton

Wearable straps and simple linkages were to be implemented in an attempt to make the wearable exoskeleton more appropriate for human interaction. The mechanical aspect of the study is a 1-DOF wearable exoskeleton that was designed using aluminum alloy 5083 to monitor the knee flexion-extension movement of the left leg and send control signals to assist the subject. This was tied to the supposed existing rehabilitation device wherein microswitches were used to detect motion intention. A clearance was found in which the microswitch lever is touching the subject's skin surface, without pressing the switch button, for knee extension. Foams were also incorporated to carry the subject's partial leg weight and not immediately press the limit switch positioned at the subject's calf, specifically during the knee flexion exercise – to ensure that the force downward is generated by the subject and not gravity. Figure 5 displays the materials used for the microswitch mechanism.

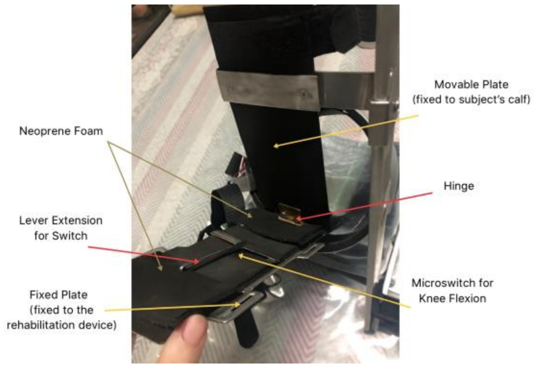
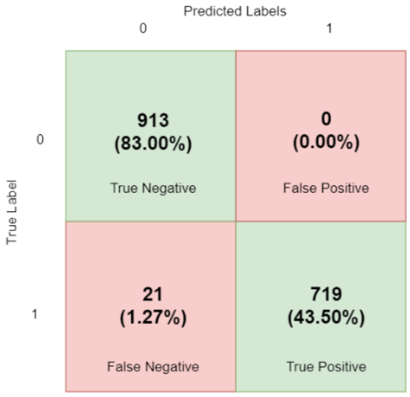


Figure 5: Materials for the microswitch mechanism for knee flexion.

3.2 Motion Intention

Figure 6 describes the classification accuracy for motion intention based on the experiments elaborated above. Results show that the developed exoskeleton is able to detect the motion intention of the subject at 98.73% classification accuracy, which satisfies the objective specified in Chapter I. Due to the peripherals that were used to detect motion intention, it was found that data for motion intention produced little to no noise as compared to using EMG sensors or accelerometers; however, they are highly reliant on the hardware design of the exoskeleton, specifically the placements of the microswitches and the clearance that was manually set for knee extension.



True Label \ Predicted Labels	0	1
0	**913** **(83.00%)** True Negative	**0** **(0.00%)** False Positive
1	**21** **(1.27%)** False Negative	**719** **(43.50%)** True Positive

Figure 6: Confusion matrix for motion intention (overall).

3.2.1 For Knee Extension

This subsection aims to evaluate the performance of the exoskeleton when executing the knee extension exercise, starting from the 90-degree angle.

Figure 7: Experimental setup: motion intention for knee extension.

With this, the exoskeleton was only activated by the microswitch positioned in the anterior part of the shin, and any input from the microswitch that was intended for knee flexion was neglected. A fixed wooden rig was used to act as the rehabilitation device for the developed exoskeleton, wherein the lower plate of the exoskeleton was tied to this fixed rig (Fig. 7). For every trial for the knee extension movement, 5 to 6 movements were performed, and a total of 4 trials were performed. As can be observed, control signals provided by the exoskeleton for motor activation primarily generated a zero output, as it could be assumed that the subject is capable of performing the exercise without any external assistance. A classification accuracy of 97.89% was achieved. A higher false value can be observed from the experiments focusing on knee extension, which can be caused by the manual measurement of clearance between the skin surface of the subject and the microswitch as shown in Figure 8.

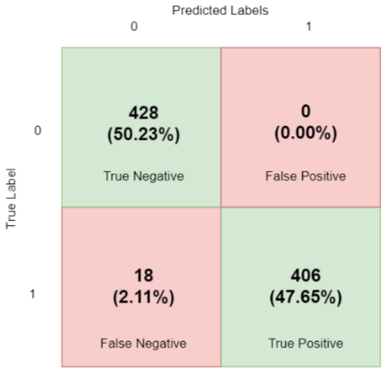


Figure 8: Confusion matrix for motion intention (extension).

3.2.2 For Knee Flexion

For knee flexion, only the microswitch located at the calf is activated for motion intention detection. Due to the design of the exoskeleton wherein a movable plate is hinged to the fixed portion of the exoskeleton calf, the weight of the leg is countered with foam placed in between the fixed and movable plates; furthermore, the microswitch would only be actuated once the user produces force downward, indicating motion intention rather than just gravity performing its duty. To test the effectiveness of the prototype, a chair was utilized to serve as the fixed portion of the existing rehabilitation device. It is vital to note that when the leg is at rest, motion intention shall not be recorded unless a force downward is produced. Figure 9 illustrates how the experimental setup was done.

Figure 9: Experimental setup: motion intention for knee flexion (180°).

A total of 4 trials were also performed by the human subject with five (5) movements per trial. This also proved that the offset of 1 to 2 degrees was achieved for the subject to activate the microswitch. Similar to the results of the previous subsection, control signals produced by the exoskeleton system are mostly zero or off. Displayed in Figure 10 is the confusion matrix for the motion intention of the subject when performing the knee flexion exercise.

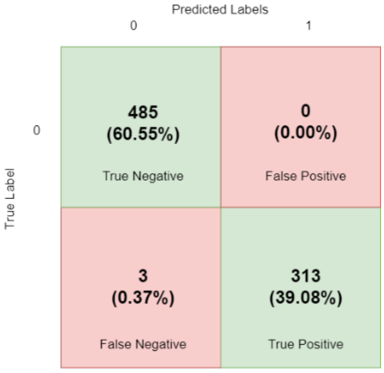


Figure 10: Confusion matrix for motion intention (flexion).

The accuracy of angle change detection was measured by performing the knee flexion-extension freely and completely, starting from the 90-degree angle to the 180-degree angle. A negative angle change denotes a knee extension movement, while a positive change indicates a knee flexion movement. A total of 4 trials (with 5 movements per trial) were performed for this subsection of the experiment. The system would only consider the angle change as a movement if it detected an angle change of at least 3 degrees, whether positive or negative.

By ensuring that the thigh portion of the exoskeleton is fixed when performing change in angle readings, the overall classification accuracy of the developed exoskeleton in detecting change in angle is at 97.55%, as shown in Figure 11. It can be observed that during the course of movement of the healthy subject's leg, there were instances that change in angle was not detected (false negative); this may be attributed or dependent to the speed of the subject's leg or leg fatigue in performing the experiment for that specific period.

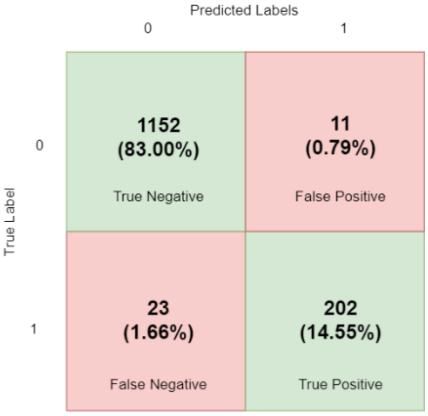


Figure 11: Confusion matrix for change in angle (overall).

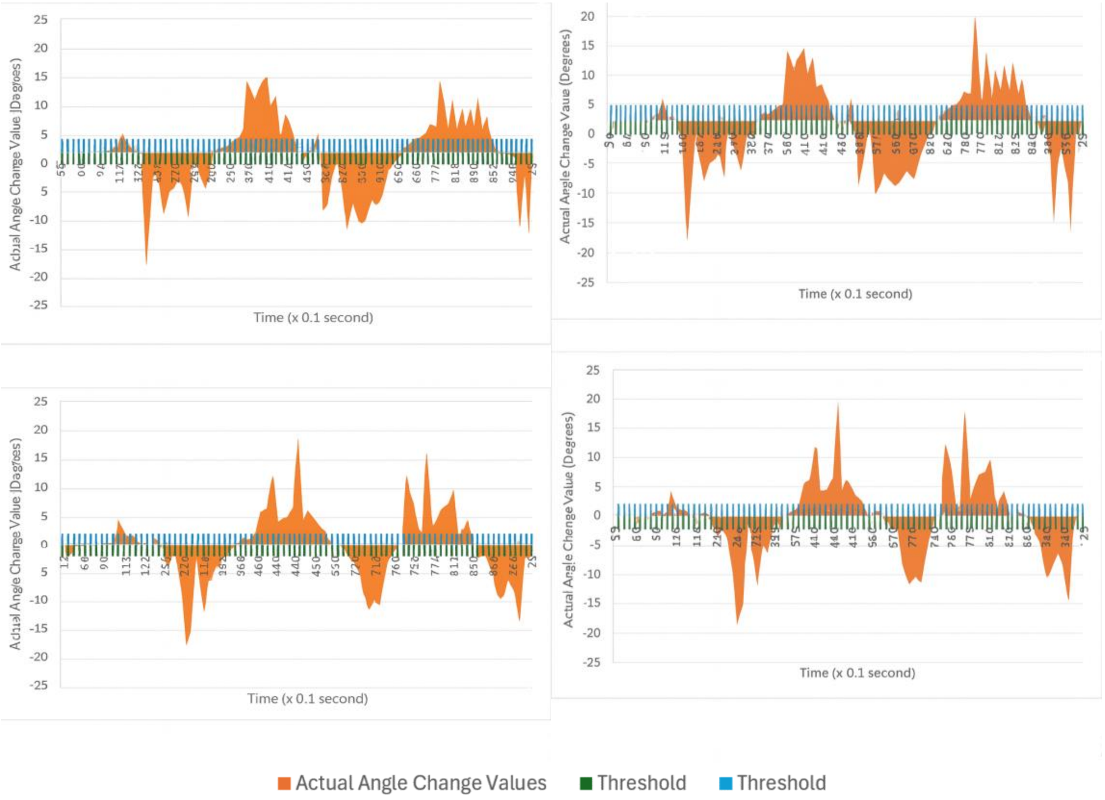


Figure 12: Change in angle vs set angle threshold.

Figure 12 illustrates the pattern of movement of the subject for all 4 trials where the obtained values for angle change were plotted along with the corresponding threshold values of +/- 2 degrees. It can be observed that for all trials in this experiment, the system only considers it as a "change in angle" if and only if the obtained value exceeded the angle threshold that was set.

4 CONCLUSIONS

Allowing for mechanical input into the exoskeleton provides a solution to noisy data often generated by sensors that do not require a mechanical operation, eliminating the risk of being affected by external factors. The obtained information for the required parameters proved that the developed system achieved a classification accuracy of at least 90%. The control signal, whose primary purpose is to instruct the connected rehabilitation device to provide assistance to the user, is dependent on the obtained values for motion intention and the reading for the angle difference. As future directives to develop further and confirm this research's initial findings, it is recommended to perform the following:

1) To implement an exoskeleton with additional degrees of freedom to imitate the actual behaviour of the knee.
2) To explore the applicability of the concept to different 1-DOF target exercises such as but not limited to bicep curls, lateral raises, etc.
3) To create a study or experiment to determine the least amount of force needed to actuate the microswitches.
4) To test the prototype with an actual existing rehabilitation device in order to provide more valuable information that would aid to the improvement of the exoskeleton.

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