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Exoskeleton for Hemiplegic Patients: Mechatronic Approach to Move One Disabled Lower Limb

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Abstract**—**The number of people suffering from hemiplegia is growing each year. This lower limb disability affects all the aspects of their lives by taking away their autonomy. This implicates their close relatives, as well as the health system to provide the necessary care they need. The integration of exoskeletons in the medical field became a promising solution to resolve this issue. This paper presents an exoskeleton designed to help hemiplegic people get back the sensation and ability of normal walking. For this purpose, three step models have been created. The first step allows a simple forward movement of the leg. The second method is designed to overcome some obstacles in the patient path, and finally the third step model gives the patient total control over the device. Each of the control methods was designed to offer a solution to the challenges that the patients may face during the walking process.

Keywords**—**Ability of normal walking, exoskeleton, hemiplegic patients, lower limb motion, mechatronics.

I. Introduction

DISABILITIES are certainly a big challenge for a person to overcome, as they take away his autonomy, and changes drastically the lifestyle that this person had before. The 2017 report of Canada Statics shows that 10 per cent of Canadians suffers from reduced mobility [1]. This can be caused by various reasons. Stroke, for example, affects each year in Canada more than 50 000 individual who can suffer from hemiplegia or paraplegia, losing the ability to move one or two legs [1]. The reduced mobility not only affects patients but their families as well as the health system as an all. They struggle from simple tasks at home, like going to the bathroom, and need intervention from their household or the health system to provide the necessary support and help. This consumes huge amounts of energy, time and resources, especially when considering the crucial rehabilitation process done in kinesiotherapy, to aid patients regain normal functioning of the affected body parts, or at least to keep the blood flowing so the muscles can be maintained as healthy as possible. Rehabilitation takes many sessions over a long period of time, which exhaust financial and human resources of the health system. Even the infrastructure of each city, including buildings, and public transportation must adapt and provide ways for persons with reduced mobility to access all structures with total ease.

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Many devices have been introduced to help patients overcome the challenges they face through their day. Crutches, wheelchairs and walkers helped patients regain some of their autonomy. In order to improve them, they have been equipped with artificial intelligence. Smart crutches can alarm from bad weight distribution, smart walkers can assist the patient to get back home safely, while smart wheelchairs can get automatically to a defined point on a map with maximum autonomy. However, all these devices have reached their full potential and yet lack satisfying many of the patient needs. On the other hand, exoskeletons have been developed for many purposes including medical ones. They first started with the goal of giving the user more strength and durability toward physical tasks. The Hardiman [2] in 1960 was the first major attempt of combining the human movements with exoskeleton robots. Although it was not practical due to the bulky design and heavy machinery, as the usage of the device resulted in violent uncontrolled motions, it pointed out some important aspects of body supply. This opened doors to various other uses in military, industrial and medical fields, especially with the rise of mechatronics; mechanics, electronics, automatics and computing. In the military field, for example, infantry troops often get tired from carrying the heavy loads and equipment they need which lower their performances in a battle. With the help of exoskeletons, they will fight fresh, as the device will allow them to go faster and further.

The introduction of exoskeletons for patients with reduced mobility had a huge impact and led to higher expectations since the device is not only designed to give them back their autonomy, but to also give them a sense of normal walking. Many exoskeletons have been developed, each one focuses on a specific case of reduced mobility. Another important aspect to keep in mind in the world of exoskeletons is the price. It can get as high as 69 000us dollar [3], which stand as a big obstacle toward mass usage, as it is not affordable for everyone especially the middle and poor class.

This article presents our exoskeleton which was designed for the hemiplegic persons. Hemiplegia tends to be a difficult case as the hardware and software needs to take in consideration the healthy leg, its trajectory and follow the user intentions correctly, unlike the paraplegic case which handles all of the walking process automatically. The device has full control over the legs but need to maintain a good posture and manage balance at all time.

The next section will discuss the related work; the solutions and ideas given with the progress made in the world of the exoskeletons. The section after will detail our solution including the hardware and software used to develop our first version of the device. This leads us to the experiment section in which we can evaluate the apparatus and its performances. Then we will finish with the conclusion.

II. Related Work

Many medical exoskeletons have been developed, each one with a different approach to the problematic but all with the same purpose, giving the patient the ability to walk without the need of an external intervention. Depending on the control methods, the way of calculating and starting the steps, we grouped them by three categories; muscular, based on brain and mechatronics.

A. Muscular

In order for a person to move, the motor center of cerebrum sends commands to the muscles. These two parts are connected via an upper and lower motor nerves. The paralyses can be caused by the damage to one of them. With this knowledge in mind, this category stimulates the muscles to restore the walking functionalities. The exoskeleton used to restore walking in [4] uses FES (functional electrical stimulation) based on EMG (An experimental technique concerned with the development, recording and analysis of myoelectric signals [13]) taken from a normal leg to make the muscles move again. This technique gives the patient a more natural feeling of walking by making him walk using his own muscles. While this can be close to normal walking, it comes with some disadvantages. Stimulating his paralyzed muscles can easily cause fatigue. Therefore, an assistance robot needs to take place in order to provide more endurance to the muscles. The exoskeleton cannot be used if his lower motor nerve is damaged, or if the patient is paraplegic.

Another approach using the same technique was proposed in [5]. Although the work was not dedicated to paralyzed people, it shows the effectiveness of an EMG based exoskeleton. In the article the exoskeleton uses a fuzzy-neuro control system that assists the user in his motion. As an input, the algorithm gets the skin surface EMG signals and the forces sensor signals installed on both the knee and the hip joints, then as an output gives the necessary torque to assist the motion. The system also implements the backpropagation learning algorithm to optimize the learning of the neural network, which gave far more interesting results.

B. Based on Brain

This category groups the different approaches that treat brain activity or visual stimulation. The researchers in [6] presented an asynchronous brain–machine interface (BMI)-based lower limb exoskeleton controlled with steady-state visual evoked potentials (SSVEPs). The idea is to execute the walk forward, turn right or left, sit or stand up by decoding electroencephalography signals of the user in real-time. The results of the experiments were promising as they showed that this type of exoskeleton is possible and can be easily used by patients with high accuracy as they require only attention and ocular movements. Although, long time usage can cause visual fatigue which can affect the SSVEP low frequency range.

Another approach which is far more interesting used the EEG (electroencephalogram), a technique that tracks and records brain wave patterns, to make it possible for the patient to control the exoskeleton with his thoughts. Much more details regarding this technique are presented in [7].

C. Mechatronics

This category groups, until now, the exoskeletons controlled manually. For example, the exoskeleton system in [8] aims to help the paralyzed, amputee and spastic patients to gain mobility using a system based on pneumatic muscles that provide controllable joint torque. The patient uses sensors attached to his fingers to give inputs to the joint sensors. For this to be achieved, a six to eight sensor hand goniometer is implemented giving the patient the control over each joint using the sensors to enhance balance for better performances and more safety. A watch dog algorithm is included to correct missing inputs required for a proper gait progression. However, the mapping system used is not easy to use. In other words, the patient has to learn to walk with his hands, which can be really tricky and not intuitive for many people. Therefore, human resources are needed in order to provide the necessary training to master the translation control. The second disadvantage is that the system cannot be used if the patient has paralyzed or amputated hands.

The exoskeleton presented in [9] is probably the closest one to ours. It uses an Arduino as a controller and four actuators to execute three main operations: sitting, standing and walking. The patient controls which operation to execute with three switches. Using two actuators on each leg, the exoskeleton moves the body in a mechanical way using relay signals. This exoskeleton is made primarily of steal, and costs around 300us dollars which makes it very affordable. Although the device includes adjustable bindings of foam, it is hard to put on and take off since the binding enrolls the entire leg. Also, the device offers no security measurements other than not executing an operation if it is already being executed. The walking is also extremely slow, one step takes up to 18 seconds to complete. And the last thing is that the walking steps are standard and do not adapt from one patient to another, which can put some patients at the risk of falling from small or big steps depending on their body.

For hemiplegic patient, the exoskeleton presented in [10] copies the lower limb motion of the abled side. Then the device generates it to move the paralyzed leg by the lower-limb power-assist exoskeleton robot. It also records the trajectory of the able leg and applies it to the disabled one. The apparatus implements many features to assure a safe step, such as adapted behavior for the leg at both swing and stable state. The exoskeleton offers torque when the support leg is not stable. ZMP (Zero Movement Point) is also implemented to prevent the user from falling, and the motion intention of the patient is well handled. However, the device offers no measurements toward obstacles that may come across the user path. Also, no kill switch is presented in case of an emergency.

The last exoskeleton that we will present [11] is mainly designed to allow paraplegic persons to gain their mobility. The device is named MindWalker, and can be controlled using two methods; triggering the remote control with push button interface or controlled by CoM (Centre of Mass) position, by leaning forward or sideways. The starting position is in an equilibrium posture. Then the weight shifting is executed depending on the intention of the user. In general, the device performed well on both controlling methods and offered good balance, however the device weighs 28 kg without batteries. It bears its own weight but it can be an issue for a patient to carry or transport the device with him.

Many devices have been created, we presented the ones that we think suited best their category and offered a good amount of details regarding their solution, so we can learn from what they presented to improve our solution.

III. Our Contribution

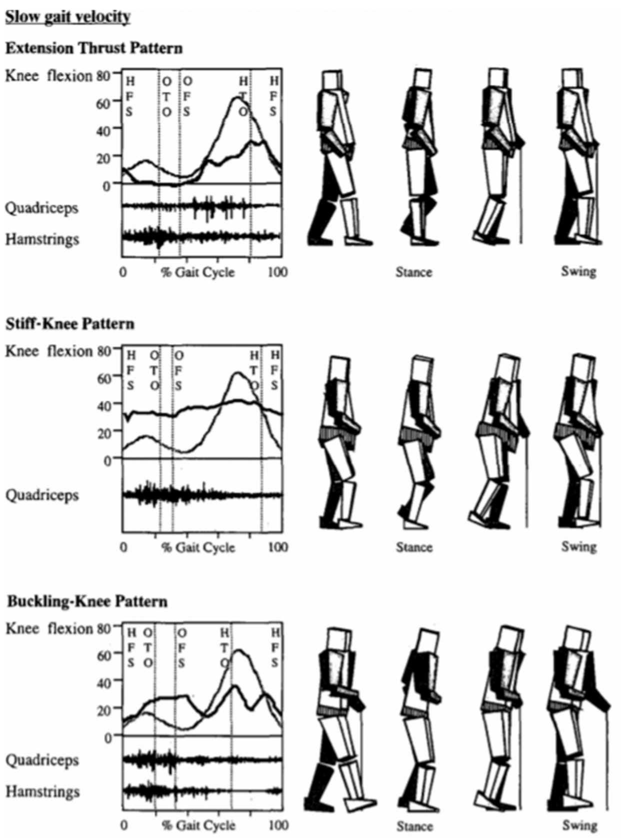

Fig. 1 Graphs and electromyographic data for motion of the knee in the sagittal plane for one gait cycle of three patients [12]

The human gait pattern is a very interesting topic. Many researchers tried to model the human walking based on various variable. The walking may differ depending on the gender, weight, height and even the psychological state of the person. The task gets even harder when the person has encountered a stroke and lost full or partial control over the lower limb motion. An interesting study done in [12] details the gait pattern in early recovery stage after stroke.

Fig. 1 shows the three motion patterns associated with slow gait velocity [12]. The article gives more details about the matter.

Taking all this information into consideration, we tried our best to implement a solution with an affordable exoskeleton capable of giving the user a stable and safe step.

Our solution is based on two linear actuators that generate the necessary movements to control the leg. The two main criteria taken in consideration when choosing the actuators type were the speed and torque. Their linear behavior makes them more stable and gives high precision. Unlike the pneumatic muscle actuators that presents a highly mathematical complex modeling challenge due to their non-linear behavior.

To control the actuator's movements, and therefore the motion of the leg, we wrote different algorithms in Python and implemented them on a Raspberry pi 0 that is connected to the actuators by a controller. The raspberry pi 0 is very convenient for our solution since it is a lightweight operating system based on the open source Debian OS. It can run multiple programing languages, among them Python that is a powerful and easy to use high level interpreted programing language.

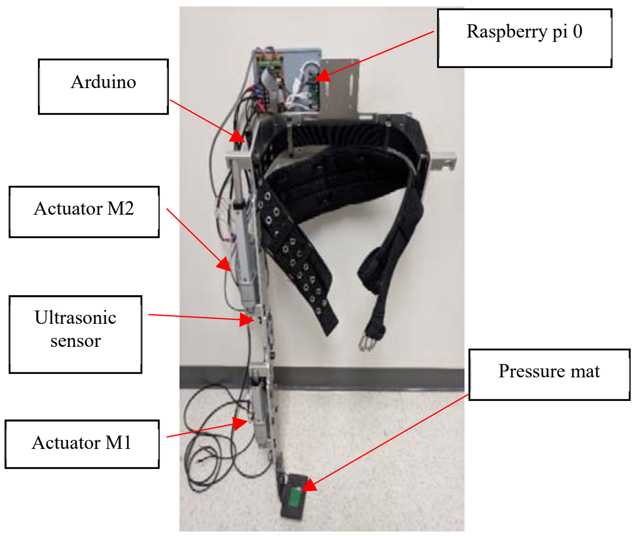

Fig. 2 Different components of the proposed exoskeleton

To make our exoskeleton practical and user-friendly, we created three different step models in Python. The step models handle challenges that the user encounter in different situations; walking, presence of obstacles, etc.

A. Direct Step

This step is the first easy step model that we created. It served as a ground to model some more complicated step models. The step allows the leg to move forward without any inclination of the knee. It uses only the superior motor. It can be used when there are no obstacles in front of the user. The step is activated using only one button installed on a crutch.

B. Mixed Step

In the presence of an obstacle, the user will not be able to move forward using the direct step. This is where the mixed step comes in play. Controlled with a second button installed on the crutch, this step uses the two actuators and allows the user to overcome some of the stumbling blocks that he may face. The step is divided into four stages. First the lower actuator (M1) bends the knee, then the superior actuator (M2) moves the leg forward. After that M1 stretches the knee and finally M2 stretches the leg. The height in which the knee should be lifted is defined for each user the first time of the usage. This way the user has control over two step models with two simple clicks on his crutch. He can then decide whether to perform a simple straight leg walk or a more complex one.

C. Free Step

The problem with the mixed step is the fixed height value for all obstacles. This makes the previous model more adapted for normal walking than overcoming the obstacles in front of the user. Therefore, we created this step model that gives the user total control over the device. It uses four buttons, each one controls an actuator separately. The two first buttons allows the forward and backward motion of M1, and the third and fourth button controls the motion of M2. We are conscious that performing more than a step with this control method is a heavy task for a patient. As a result, this model will be used to learn the different foot trajectories for a next automatic calculation of the trajectory.

We also implemented a few security measurements in our solution to protect the user, especially from falling. The principal security measurement is an emergency stop button installed on the crutch. The button stops the actuators immediately so the user can regain control over the device. We also predefined a maximal and minimal value for the actuators to make sure that the user does not get injured from dangerous maneuvers. Moreover, we installed two sensors; a pressure map and an ultrasonic sensor (see Fig. 2). The first sensor prevents the activation of the step if the disabled leg of the patient is engaged in his balance. The second one prevents lunching the step if the distance between the leg and an unsurmountable obstacle in front of the user is lower than a predefined threshold. The values returned from the two sensors are retrieved by the raspberry pi 0 via an Arduino.

After summarizing the different components and functioning of our solution in this section, the next one will show us the effectiveness of our device.

IV. Experiments

The experiments were executed with the help of six healthy students. We asked them to be as objective as possible and try to simulate a hemiplegic case, by completely following the motion of the device. However, we cannot exclude that the participants contributed to the step due to their non-neglected muscle activity.

Tests on real hemiplegic patients will be done once we make sure that all the step models work properly. This way we can ensure the patients' safety and help them regain their autonomy in a proper way.

Fig. 3 Our Exoskeleton carried by a voluntary student

We attached the exoskeleton to the lower limb using foam attachments for a soft contact between the leg and the device. Then we used a belt to attach the hip part (Fig. 3).

To objectively judge the performance of the device, we fixed four criteria. First is the manipulation of the device that needs to be easy and intuitive for the users, the second criteria are the efficiency of the step model, as well as the stability of the device. The step also needs to be comfortable in order to allow long distance walking and finally the sensation that the user gets from the walking experience as an all (SNW: Sensation of normal walking).

The experiments consisted of executing the three step models. Participants were then asked to rate each criterion for the three models on a scale of five, with five being the best.

TABLE I
Results of the Mean of Values Given by the Participants for Each Criterion

Step Model	Manipulation	Efficiency	Comfort	SNW
a	5	4	3.5	4
b	4	3.5	3	3.5
c	2	2	1.5	2

The best rated step model was the direct step. Activating it requires only one click. It is efficient and comfortable since only the upper motor is involved. It takes less time to complete the step than the other models, which makes it more practical for walking long distances as long as no obstacles are presented.

The mixed step is also easy to manipulate, except that defining the height for the first time was not as intuitive as we conceived. Once the height was fixed, it was not possible to change it via the interface on the crutch. The efficiency of the step was quite good, the lower motor bends the knee to the specified range, then the upper motor moves the leg forward and so on. Although the step took longer than the previous model to complete due to the implication of both the actuators, it is practical for medium walking usage. On the other hand, the free step scored the lowest rates on all the criteria which is understandable due to the complexity of the model. Although the users had total control over the device, manipulating it was not an easy task. The participants felt confused on how to perform the step in the first usages. They kept balance on their healthy leg and crutch with the supposed disabled leg lifted from the ground trying to figure out the next move. This can be very dangerous with real patients, as they can easily lose balance and fall. Once the participants got familiar with the control method, they were able to walk freely with the exoskeleton. The model gave us more information on the gait pattern that the users felt suited them best.

The security measurements on the device worked fine. Pressing an activation button with the supposed disabled leg on the ground triggered nothing. The user had to shift the weight toward the crutch and the healthy leg in order for the device to lift the disabled leg from the ground. This way the patient will not fall due to non-proportional weight on the legs when walking with the exoskeleton. When standing close to a wall, the ultrasonic sensor prevented the actuators from moving the leg. This assured that the user will not hurt his leg by hitting an obstacle during the phase of the step.

After many experiments, the attachments holding the leg to the exoskeleton started to fall. The bindings used will surely be changed to something more resisting. All the participants complained from a pressure exercised by the exoskeleton on the lower part of the back when the upper motor was operating. This issue will be fixed by adjusting the hip part in our device.

In general, the experiments allowed us to manipulate closely the device and explore the mechanics behind the human walking. It also allowed us to collect important data that can be used in our further researches on automating the walk. The present exoskeleton can be used to move the leg and assist the walking process. However, the tests also brought to light some issues that will be fixed in our next version such as the pressure exerted on the lower back when moving the upper actuator.

V. Conclusion

In this paper, an exoskeleton that offers three step models for hemiplegic people is proposed. As users may encounter different challenges when walking, it is more practical to offer a solution dedicated for each challenge. The step models implemented differs in terms of the control method used. Security is also one of our main concerns, which is the reason we installed a pressure mat and an ultrasonic sensor. The results were promising even though they showed many issues that the device had. This version was our initialization to the word of medical exoskeletons. It helped us learn more about the mechanics and software employed in these assistive devices. It also gave us the opportunity to test many ideas we had. Our next version will propose a more lightweight and developed exoskeleton that fixes all the issues present in this version. We will also implement artificial intelligence in order to automate the process of walking.

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