



# Controlling a Lower-Leg Exoskeleton Using Voltage and Current Variation Signals of a DC Motor Mounted at the Knee Joint

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## Abstract

Powered exoskeleton technology helps turns dreams of recovering mobility after paralysis into reality. One of the most common problems encountered in the use of powered exoskeletons is the detection of the motion intentions of the user. Many approaches to conquering this problem have been developed using Electromyography (EMG) sensors, Electroencephalography (EEG) sensors, Center of Pressure (COP), and so forth. When a method, such as the surface EMG, is contaminated with noise during acquisition, it is important to process that raw EMG signal. Doing so usually takes time, and time delays in such a system can lead to a loss in synchronization between the wearer and the exoskeleton. Many algorithms have been developed for data acquisition and the filtering of raw EMG signals as well as accelerometer data. Our approach involves designing an almost sensor-less low limb exoskeleton that is powered by an electric Direct Current (DC) motor, and the same motor is used to detect motion via monitoring the voltage and the current variation. Experimental results are obtained for the actuating knee flexion-to-extension then extension-to-flexion of a sitting person using the National Instrument (NI) MyRIO as a data acquisition system with NI-LabView. The results support the hypothesis that the developed system can detect human motion and drive the motor in the necessary direction without the use of uncomfortable electrodes (sensors) and their connections. Additionally, the system supported the wearer to move his leg up (extension) without having too much effort to do so. In order to identify muscle activation with the change in the angle along the sagittal plane, an accelerometer has been attached to the system. The proposed approach could help open a new pathway along which researchers could develop low-cost and easy-to-wear powered exoskeletons which could emulate precisely the normal gait of a human.

**Keywords** Exoskeleton · Lower limb · DC motor · H-bridge · Sensor-less · EMG · LabView · Accelerometer · Current variation

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## Introduction

Powered exoskeletons are mobile machines consisting primarily of an outer framework used by a person, a powered system of motors, hydraulics, pneumatics, levers, or a combination of technologies that deliver at least part of the energy for limbs movement. This framework enables the wearer to get a better lifestyle such as boosting their strength and endurance. This innovative invention provides disabled patients an unprecedented degree of freedom that wheelchairs cannot provide [1]. It is always designed as an external mechanical structure whose joints correspond to those of the human body or limbs. So, it can be used by paralyzed patients for walking and can be useful for healthy people by giving them superhuman capabilities. Due to their characteristics and potential exoskeletons could be used in several fields: in medicine, industry, construction, military and rescue task [2–6].

Modern-day hardware for exoskeletons and prosthetics is becoming lighter, stronger, and power dense, the current approaches to the control of powered leg devices are rudimentary and driven by finite-state machines with several phases such as swing, stance, heel-strike, and toe-off. Each of these approaches contains numerous tunable parameters that are specific to each user and typically require the use of additional aids such as crutches to be used safely [7]. There are several medical electrical equipment exoskeletons developed for upright walking of paralyzed people. A good example is the ReWalk exo, which has been developed for Spinal Cord Injured (SCI) patients. As a patient-worn backpack device, ReWalk is a self-contained exoskeleton which uses rechargeable batteries to drive the hip and knee joint motors. It uses a tilt sensor to compute the trunk angle and a wristwatch-style controller to activate different motion modes such as stand-sit, sit-stand, or walking. ReWalk has been designed to be used by persons weighing less than 100 kg, height in the range of 157–193 cm, and having the adequate upper-body strength to use the medical exoskeleton. These constraints can limit its range of end users [8]. Another example of SCI applications is the Indego exoskeleton developed and commercialized by Vanderbilt University. It offers a modular mechanical design which consists of three parts, namely a hip brace, two thigh frames, and two shank frames, which can be assembled quickly for putting the exoskeleton on. It has been developed to be used with a conventional set of ankle-foot orthoses and is claimed to be easy to put on, take off, and to be adjusted for good fitting single-handedly [9]. In 2013, Ghent University exoskeleton: “WALL-X” was the first exoskeleton that allowed to reduce the metabolic cost below the cost of normal walking. This result was achieved by optimizing the controls based on the study of the biomechanics of the human-exoskeleton interaction [10]. Many technological challenges face the future and the development of powered exoskeleton to build a suit that is capable of quick and intelligent movements, yet is also safe to operate without extensive training. The power supply [11], power control and modulation [12], adaptation to user size variations, easy to wear, and detection of unsafe/invalid motion [13] are also some of the large problems that researchers work on to reduce these limitations.

The international safety regulatory requirements (published by ISO/IEC) for medical and non-medical exoskeletons are different and must be complied with for successful commercialization. For medical exoskeletons, such regulations are still underdeveloped by the joint working group IEC SC62D and ISO TC299 JWG36 (medical robots for rehabilitation), whereas for non-medical exoskeletons, ISO TC299 WG2 (personal care robot safety) has produced and published the safety requirements for physical assistant robots (restraint and restraint-free types). It is important to be aware of these standards and what is emerging in a regulatory sense, that is, is the wearable robot a medical electrical equipment for patients or a personal care

exoskeleton for healthy persons, so that the correct risk assessment and risk reduction can be carried out for non-medical exoskeletons or appropriate risk management carried out for medical exoskeletons. This means identifying and applying relevant medical device or machine safety standards [9].

In this paper, we are going to focus on the medical exoskeleton. Our target is to help and support patients who are not fully paralyzed but are able to make any slight movement in the desired direction. Typically, exoskeletons have a huge number of sensors attached to the body of the wearer such as Electromyography (EMG) sensors, Electroencephalography (EEG) sensors, Center of Pressure (COP), or any pressure sensors that require a complicated signal processing and could lead to an overshooting problem [14]. The overshooting problem is due to the lagging between the wearer’s body and the suit limb position, and in consequence of that, it leads to unwanted movements which can injure the wearer [15, 16]. Moreover, the need to have training data in neuro-interfacing exoskeletons in medical rehabilitation increases the design challenges because of the complexity of the interaction between electromechanical structures and the human body, either at the physical or at the control level [17–20].

Therefore, we made an alternative design to get more efficient leg exoskeleton, by reducing the number of sensors used, which led to reduce the design complexity and the overshooting problem. The new design has been achieved by using a geared DC motor mounted on the knee joint of the exoskeleton’s leg. The basic principle of the developed system is to detect the user intention of movement by monitoring the developed voltage and current at the mounted motor. For example, exoskeleton system can detect the initiation of the leg movement by detection of the motor’s generated voltage, after that the system can make a decision to start the exoskeleton motion or not depending value of the generated voltage.

In addition, the system stops motion depending on the variation in motor current, which can be detected through a shunt resistor connected to the H-bridge circuit that is used to allow the motor to rotate in two directions. Then, the generated voltage and current variations can be measured and processed using National Instrument (NI) MyRIO embedded system programmed using NI-LabView [21]. Finally, an accelerometer is mounted near the motor joint to provide the system feedback information about the leg angle and position.

In this paper, detection of knee flexion-to-extension and extension-to-flexion movements for a sitting person, withholding the leg up for 1 s is proposed. A motor is mounted on the knee to support the exoskeleton wearer and will be also used to detect the desired motion direction. The authors in this work illustrate that almost sensor-less, low cost and easy to implement powered exoskeleton that uses DC motors, can be developed to support and enhance the human motor functions. The results support the hypothesis which expresses that the developed system can detect human motion and drive the motor in a necessary direction. The

three input signals (voltage, current, and angle) are the key signals that enable the user to control the exoskeleton according to his or her will. A great thread to such systems is to reduce the overshoot problem, and of course to mimic the normal human gait as much as possible. The normal motion without exoskeleton is usually compared with the motion with it, and researchers try to minimize the delay (error) between the two motions. In this work, a simple open loop controller has been used to control the motion, which resulted in a low error between the reference extension pattern and the exoskeleton actuation performance has been noticed. Fuzzy logic or Proportional–Integral–Derivative (PID) controller can lead to minimizing this error more, as many researchers try to minimize this error [22, 23].

The proposed design can be used for support purposes in general whether for medical or non-medical uses. For medical uses, the system can help disabled to walk freely without a wheelchair which makes mobility limited. For non-medical uses, such a system can help normal people to have extra power or to feel comfortable when doing some hard labor.

This paper is organized as follow: Section 2 includes a brief description of the current variation in the motor. Section 3 describes the experimental methodology along with the developed algorithm for data acquisition H-bridge schematic and a short discussion of the tested motion. The results are presented and discussed in Section 4. Finally, conclusions have been drawn by combining all the important points of the study.

### Motor current variations

As mentioned, a motor is mounted at the knee joint of the exoskeleton, as shown in Fig. 1. This motor has two functions: to work as a sensor by monitoring the voltage and current variations attached to the motion and to work as a motor to support the movement of the exoskeleton wearer.

In case of the motor action, the electrical power input ( $E_a * I_a$ ) to the magnetic field by the electrical system must equal to mechanical power ( $T * \omega_m$ ) developed and withdrawn from the field by the mechanical system [24].

$$E_a I_a = K_a \varphi \omega_m I_a = T \omega_m \tag{1}$$

where  $E_a$  is the voltage in all the motor turns,  $I_a$  is the armature terminal current,  $K_a$  is known as the machine (or armature) constant,  $\varphi$  is the flux per pole,  $\omega_m$  is the mechanical speed, and  $T$  is the total torque developed. By analyzing the torque at the knee joint as described in Fig. 1, we find:

$$T = rF \tag{2}$$

where

$$I_a = \frac{T}{K_a \varphi} \tag{3}$$

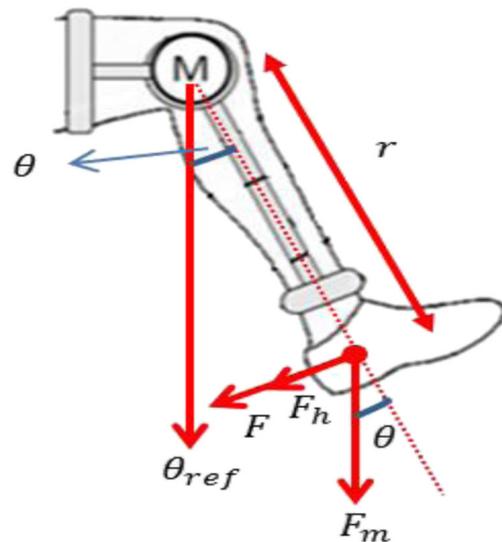


Fig. 1 Mounted motor, reference angle, and forces

then

$$I_a = \frac{rF}{K_a \varphi} \tag{4}$$

where  $r$  is the length of the lower leg, and  $F$  is the total force perpendicular to the leg axis. Assuming that the total force ( $F$ ) at the ankle is equivalent to the force caused by the center of mass of the lower leg ( $F_m$ ), and the force of resisting or assisting the exoskeleton motion by the wearer ( $F_h$ ). So:

$$F = F_m \sin(\theta) + F_h \tag{5}$$

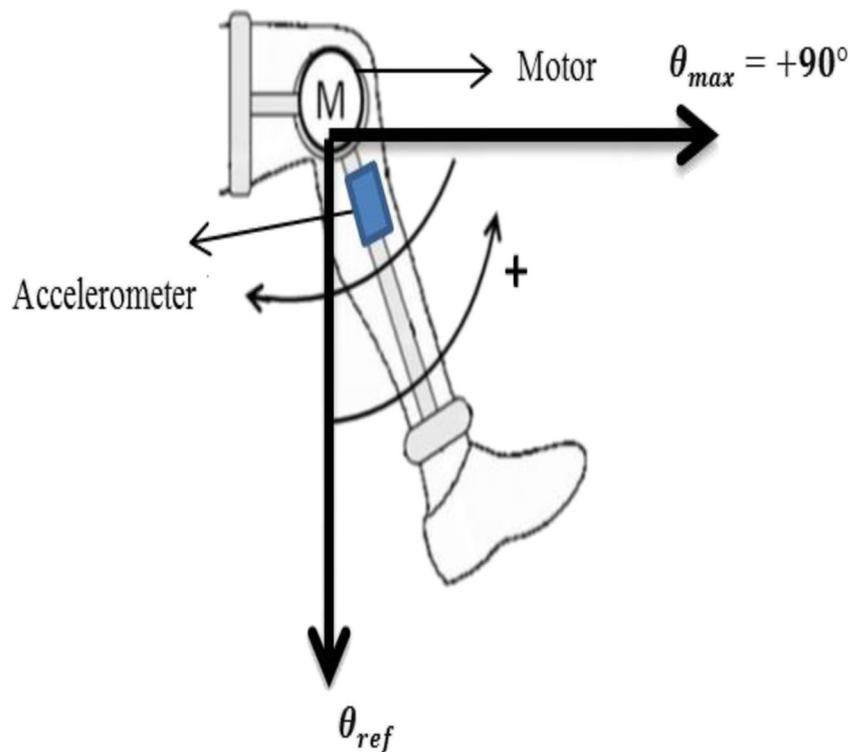
where  $\theta$  is the angle between the leg axis with the reference angle  $\theta_{ref}$ , as depicted in Fig. 1. From Eq. (3) it is clear that the current ( $I_a$ ) is directly proportional to the torque ( $T$ ), where  $r$  is constant for the same person, from Eqs. (4) and (5), the torque ( $T$ ) can be increased or decreased with the increase or decrease of ( $\theta$  or  $F$ ).

If the exoskeleton wearer has resisted the exoskeleton motion, then  $F_h$  will be in positive. If he assisted the motion,  $F_h$  will be in negative. In other words, from Eqs. (4) and (5), we can see that resisting the exoskeleton motion will increase the motor current ( $I_a$ ). If the wearer wants to move in the same direction of the exoskeleton (no resistance) the motor current will be decreased.

### Experimental methodology

To study and analyze the relationship between the relevant parameters (induced voltage, motor current variation, and position angle), the following experiment has been performed. As shown in Figs. 2 and 3, the sitting position is assumed to be the initial position and the angle of the vertical leg to the ground is assumed to be the reference angle. The extension

**Fig. 2** Lower leg extension and flexion tested motion



of the leg is assumed to be in the positive direction, and thus the maximum rotation angle is  $+90^\circ$ , while flexion is assumed to be in the negative direction.

The material used for the mechanical structure is Polylactic acid. The structure printed using a 3D printer. The thickness was chosen to have thigh and shank relatively strong enough to complete the electrical measurements required for this experiment. The total weight of the mechanical system for the right leg is 1.2 kg.



**Fig. 3** Developed exoskeleton for extension and flexion motion test

The results in this work have been taken for non-medical application. The “ISO TC299 WG2” safety issues such as: robot stopping, mechanical limits, and safety-related force control have been taken into consideration during the test. Other safety requirements have been ignored due to the nature of the test which focuses on electrical measurements. For example, “hazards related to charging battery” has been ignored due to the location of the battery, as shown in Fig. 3.

Rechargeable battery 12 V/4AH lead acid was used. As the experiment was performed for extension and flexion motion for a seated person, the battery location is not an issue. The battery and some other components were placed on a table close to the exoskeleton wearer, as shown in Fig. 3.

The experimental methodology is represented in this section of this paper. The proposed flow chart of the experiment is illustrated in Fig. 4. Whether there is a leg movement or not, the induced voltage signal of the DC motor is monitored continuously (read) until the voltage reaches a predetermined threshold value due to the initiation of leg movement. If the voltage reaches the threshold value, the motor will turn on in the same direction of the leg movement.

While the motor is ON, the system begins to monitor the motor current. Any resistance from the wearer or any sudden stopping of the leg movement will increase the motor current; whenever the current exceeds the positive threshold value, this reading indicates that the motion in that direction is no longer desired. Therefore, the system will make a decision at this point to turn the motor OFF. After some delay, the system will be ready to detect any new motion and repeat the cycle. The

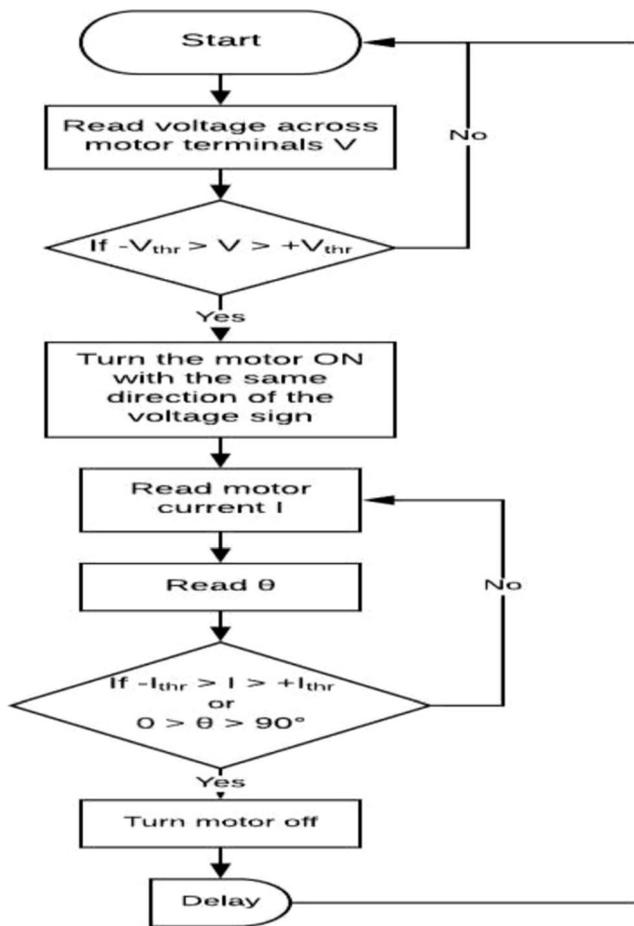


Fig. 4 Flow chart of the sensor-less exoskeleton leg

delay is necessary to dissipate the current in the motor coil after the motor is turned OFF and has been arbitrarily chosen to be long enough to ensure that the motor dissipates the current completely. In fact, after the detection of the motion has occurred and the motor has been turned on, the variation in the current contains all of the information required to identify the willingness of the exoskeleton’s wearer.

For designing and controlling the leg exoskeleton, a DC geared motor with a 101 RPM, 30:1 gear ratio, and a stall torque of 3.28 kg-cm at 12 V has been selected. As well, the following components have been used: an H-Bridge, a shunt resistor, an accelerometer, and NI-MyRIO-1900. LabView has been used to analyses and control signals. The DC motor is mounted on the leg exoskeleton knee joint. The induced voltage in the motor due to a slight leg motion is measured by the NI-MyRIO Analog to Digital Converter (ADC), which then, depending on the voltage threshold value, feeds information back to the motor to turn it ON. The motor is driven by an H-Bridge, as shown in Fig. 5. A shunt resistor is connected to the motor’s negative terminal to monitor the current. An accelerometer is attached to the bottom of the leg to measure the angle.

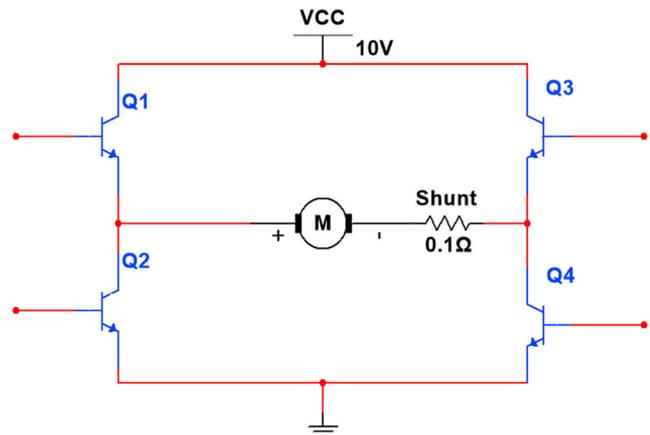


Fig. 5 Schematic of testing H-Bridge circuit with motor and shunt resistor

## Results and discussion

### Overview

The analytical and experimental results will be discussed in this chapter. As mentioned, LabView has been used for measurements. All results, i.e., voltages, currents, and angles, will be analyzed with respect to time. Equations (4) and (5) show that the current is directly proportional to the angle  $\theta$ . So, the relation between  $\theta$  and time should be clarified.

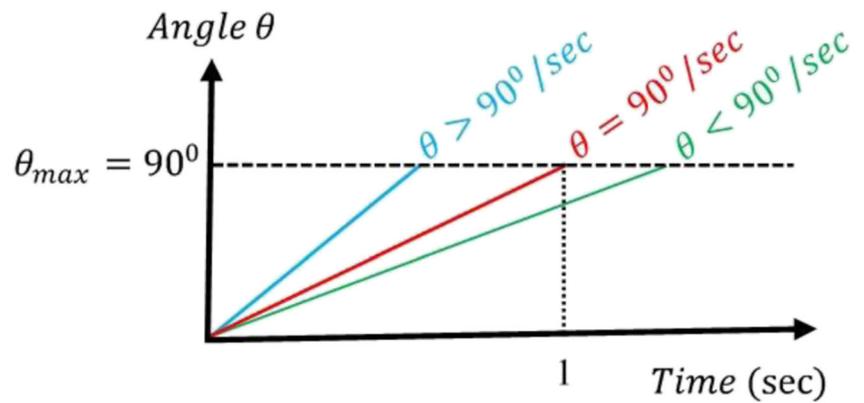
For simplicity, the angle of motion has been considered to be linearly dependent on time, as illustrated in Fig. 6. Obviously, different angular speeds have different slopes. Mechanically, the maximum angle is limited by  $90^{\circ}$  and has been electrically limited by  $85^{\circ}$  for additional safety. In the forthcoming results, all of the measured data will be displayed with respect to time.

## Experimental results

### Repetitive extension/flexion motion

The flow chart in Fig. 4 shows that the system has been tested for motors which are fully turned ON or completely turned OFF. In other words, no control system was applied to make a motor work at variable speeds. Figure 7 shows how the waveforms of voltage, current, and the angle behave for repetitive extension and flexion motions. Each extension-flexion motion is called a cycle. This repetitive waveform shows the results for arbitrary motion which is sometimes stopped by reaching the maximum or minimum angle and sometimes by reaching the upper or lower current limits. It can be seen that three types of waveforms are needed to illustrate the system behavior:

Fig. 6 Motion angle versus time



terminal voltage across the motor, the motor current variation, and the angle, as shown in Fig. 7a, b, and c. Thresholds for the voltage, current, and angles have been arbitrary chosen in a way to make the results obvious for analysis. The thresholds are chosen as follows:

- $V^+$  is the voltage threshold in the positive direction = +0.8 V
- $V^-$  is the voltage threshold in the negative direction = -0.8 V
- $I^+$  is the current threshold in the positive direction = +0.7 A
- $I^-$  is the current threshold in the negative direction = -0.7 A
- $\theta_{max}$  is the maximum angle of positive direction = +85°
- $\theta_{min}$  is the minimum angle of negative direction = -20°

**Extension/flexion motion stopped by angle limits**

Figure 8a, b, and c show the results for one cycle of motion which was stopped by reaching the maximal

angle(s). It means that the wearer did not resist the motion of the motor and that he desired the motion in that direction until his leg reached the angle limits. It can be seen from the angle waveform that the leg was in the reference position before time ( $t \approx 30$ ) when the reading was  $0^\circ$ . From the voltage and current waveforms, we note that at ( $t \approx 30$ ), motion in the positive direction has been detected. At ( $t \approx 35$ ), the leg reaches the maximum angle  $\theta_{max}$ , then the system forces the motor to stop the motion by disconnecting the power supply to the H-Bridge as the voltage reading becomes zero volts. At ( $t \approx 47$ ), motion in the negative direction has been detected, i.e., both voltage and current are negative until reaching the minimum angle  $\theta_{min}$  at ( $t \approx 54$ ).

**Voltage start/current stop the motor**

Figure 9a, b, and c focus on results for an extension motion. The terminal voltage graph shows that a slight motion at ( $t \approx 8$ ) is detected. The motor works as a generator in this case and converts the motion to a voltage. Whenever the generated voltage exceeds  $V^+$ , the system will connect the motor to the power supply to start

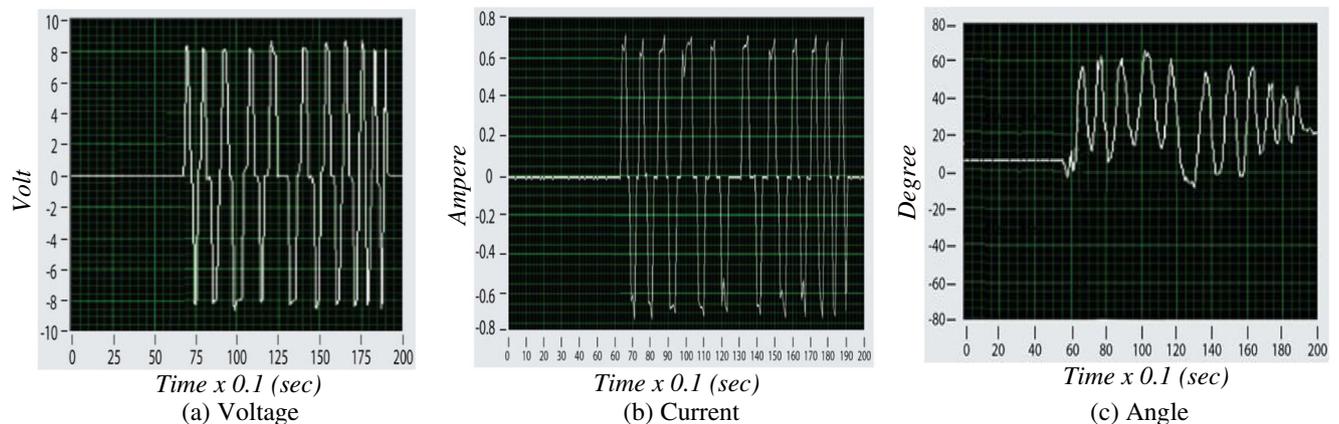
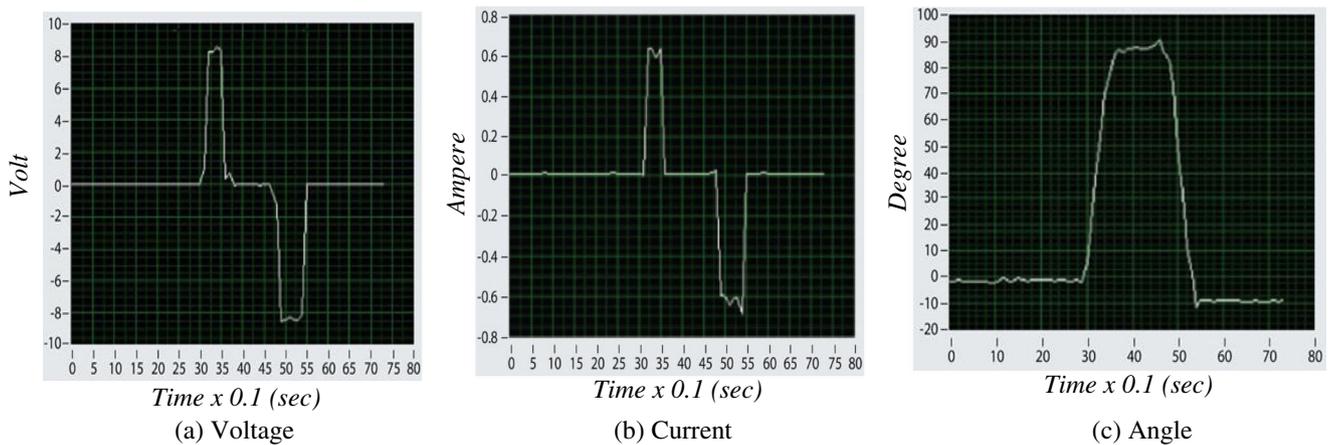


Fig. 7 Voltage, current, and angle waveforms for repetitive extension/flexion motion



**Fig. 8** Voltage, current, and angle waveforms for extension/flexion motion stopped by angle limits

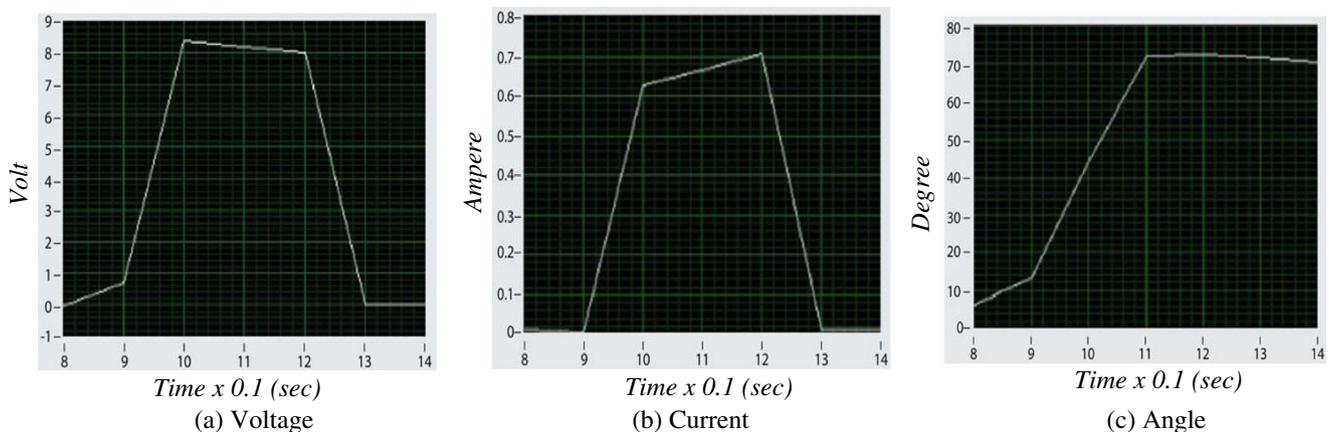
supporting the motion in the positive direction. Such an occurrence at ( $t \approx 9$ ) results in a jump in the voltage to almost 9 V, which is equal to the power supply voltage of the H-Bridge. After connecting the power supply to the motor, the current starts to increase inside the motor winding, as shown in the motor current graph in Fig. 9b. From ( $t \approx 9$ ) to ( $t \approx 12$ ) the current keeps increasing, as Eq. (4) shows that the current is directly proportional to the angle  $\theta$ . At ( $t \approx 12$ ), the motion in the positive direction is no longer desired. The exoskeleton wearer resists the motion in that direction, resulting in a large motor current exceeding the  $I^+$  value. Therefore, the system decides to stop supplying the motor. This decision takes place at ( $\theta \approx 72^\circ$ ), as shown in the angle graph in Fig. 9c.

Figure 10a, b, and c are similar to the previous case for an extension motion. However, the motion in this case is flexion motion, as both the voltage and current have negative values.

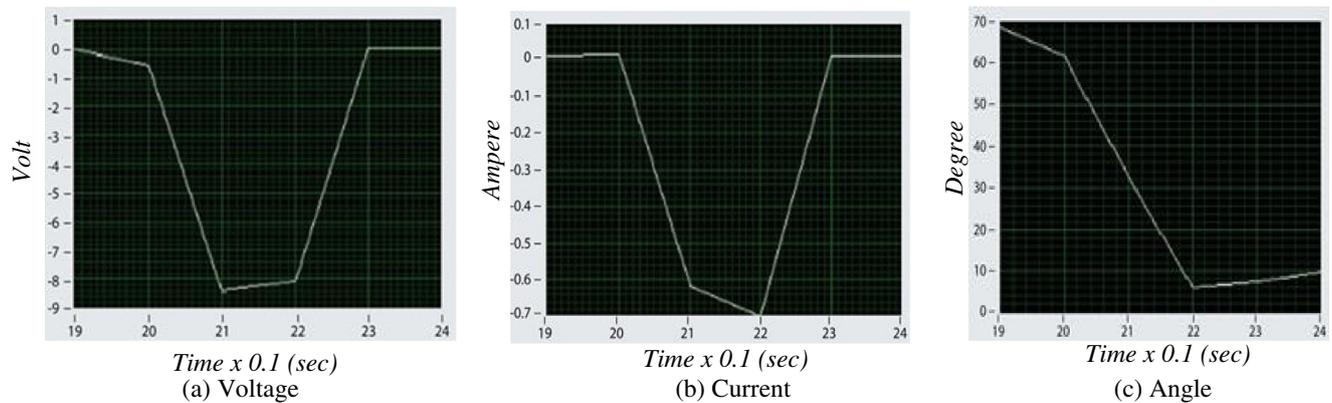
**One cycle comparison with normal extension/flexion motion**

In this subsection, the obtained knee angle result from the user’s motion without the exoskeleton is compared with the

same motion with the actuated exoskeleton, as shown in Fig. 11. As mentioned previously, the system is controlled by an open-loop controller, and the tested motion was executed for one cycle of motion: extension, holding at the maximum angle for (1 s), then flexion. By considering this tested motion, the following differences can be noted: First, the slope for the exoskeleton before ( $\theta \approx 4^\circ$ / blue circle) is less than that for the normal motion. The reason for this difference is that there will be quite an extra load on the user before the exoskeleton is actuated since the exoskeleton and geared motor are heavy. This error can be minimized by controlling or reducing the positive threshold voltage. Second, the slope when the leg is rising is less without the exoskeleton, and this result is expected since the exoskeleton provides a measure of support for the exoskeleton wearer. The last issue is the response when the user tries to keep his leg up for 1 second. An almost flat response can obviously be seen with the actuated exoskeleton, whereas a non-flat response (almost triangular) can be observed without it. These responses are the result of the user being unable to keep his leg up in a stable way without the exoskeleton, while he can do this with the exoskeleton acting as a kind of support.



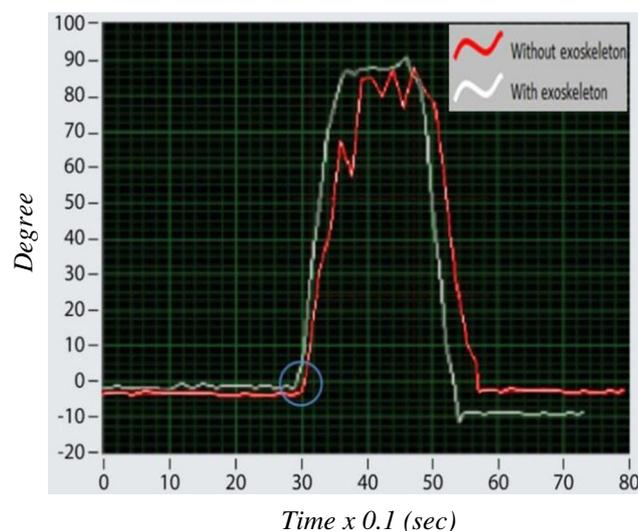
**Fig. 9** Voltage, current, and angle waveforms for extension motion stopped by positive current limits



**Fig. 10** Voltage, current, and angle waveforms for flexion motion stopped by negative current limits

## Discussion

This work is a proof of concept that the signals: voltage, current variation, and the angle have enough information about the intention of the exoskeleton wearer. The system provided real support to the wearer for the proposed motion. The non-smooth motion has been observed, this is due to using fixed thresholds values. As high fixed threshold values make the system useless as the user should have more effort until the system start responded to his motion intention. While low threshold values make the system very sensitive and behave in a hysteresis way. A more advanced controller such as PID or Fuzzy logic controller is highly recommended in this work to have dynamic threshold values. Despite, using moderate threshold values such as the values mention in Section 4.2.1 supported the user to move his leg exactly in the desired direction.



**Fig. 11** Knee angle for normal motion vs. motion actuated by an exoskeleton

## Conclusion

In this paper, an almost sensor-less, low-cost, and easy-to-implement leg exoskeleton was designed to support and enhance human motor functions. The proposed prototype was analyzed and experimented on via the use of a healthy subject. The evaluation of the system showed promising results.

EMG sensors, along with their data acquisition system and complicated neuro-connections were eliminated, i.e., the user's intended motion can be now be detected entirely by DC motors connected at each joint. Just a slight initiation of leg movement is capable of triggering the motor to raise or lower the leg. As was shown in the experimental results, the motor can be turned OFF automatically while the leg is completely extended or completely flexed as well as when the subject needs to stop the movement before reaching the maximal angle in either direction. In a future study, a higher-powered DC motor with a control system, such as a PID controller or Fuzzy logic controller, could make the motion smoother and more comfortable to the user by controlling the motor speed and to have dynamic threshold values instead of static threshold values. Minimizing the current dissipation time in motor windings is also necessary in order to make the response time of the system faster, as the other parameters in the new system are extremely fast at responding where no complicated signal processing is needed. Furthermore, machine learning algorithms could be implemented in order to adapt the leg exoskeleton to the wearer's specifications. Based on the achieved results, the design of a full exoskeleton for all degrees of freedom for lower-body limbs can be accomplished.

## Compliance with ethical standards

**Conflict of interests** The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Ethical approval** All procedures performed in studies involving human participants were in accordance with the ethical standards of the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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