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Research paper

The Development of Lower Limb Exoskeleton for Stroke Patients

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Abstract

A new set of lower limbs exoskeleton was developed for the use of hemiplegic stroke patients. The movement of the exoskeleton according to normal gait cycle was driven by two direct currents (DC) stepper motors. These motors incorporated with the worm-gear to provide forward-reverse rotation, constant power and high torque at lower speed. It will be used to drive the hip and knee movements to support the stroke patient in restoring and regaining physical lower limb movements. Hip and knee movements exercise is important to improve blood circulation as well as to avoid the deterioration of leg muscle of the paralyzed patients. In this paper, a system was tested on 6 healthy subjects with different height and weight. The exoskeleton movement was controlled through an android application by Arduino controller. The result showed that every subject, despite having different height and weight, gave similar results in the angle but with different execution time, depending on their walking pattern.

Keywords: *Arduino; Gait cycle; Stroke; Lower Limbs Exoskeleton*

1. Introduction

In 2013 World Health Organization released an official statistical data stating that the number of stroke patients is increasing drastically over 40 years since 1970 [1], [2]. In Malaysia, stroke is among top five leading cause of death among Malaysian citizens [3]. Stroke is a serious threat to human health as a common disease with the characteristics of high morbidity, high disability rate and high fatality rate. About 75% of the surviving stroke patients have obstructions of limb ability and language function, which will seriously affect their quality of life and can place an enormous burden to their families and society [4]. Although all strokes are different, there are some common physical problems that many people experience, such as problems with vision, problems with controlling bowels and excessive tiredness. Many people experience muscle weakness or paralysis after a stroke, which can affect their mobility and balance [5]. This usually happens on one side of their body and can cause a lot of pain and discomfort.

Rehabilitative therapy must be conducted as soon as possible as early attention to the weak limbs can greatly improve the chances for a successful recovery [6]. It is also important to improve the blood circulation, maintain joint flexibility and regain strength in the affected limbs. Thus, a grand challenge is to develop the means for restoring functions, including both movement and sensation, and for eliminating pain for those with paralysis [7], [8].

In this paper, a set of human leg exoskeleton for the lower limb was developed to aid the rehabilitation process for patients to regain their ability to walk following normal human gait cycle [9]–[11]. Gait cycle is part of engineering which deals with the study of motions of the human body while walking. It deals with the physical dimensions involved and responsible for the walking manner of the human subject. Gait can be further classified into two phases; the stance phase and the swing phase.

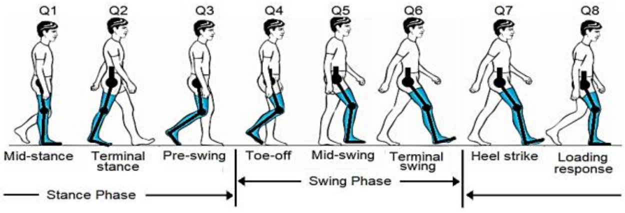

Fig. 1: Exoskeleton phase of gait cycle

Figure 1 shows the exoskeleton phases of a gait cycle for as normal human gait cycle which consists of 60% stance phase, which is generally categorized by the time when the ankle foot orthosis (AFO) foot is in contact with the ground, and 40% swing phase, which can be defined as the period of time where the AFOs is not in contact with the ground.

Exoskeletons are wearable systems, which can help the human wearers perform a variety of normal daily living motion tasks such as walking, carrying loads, ascending/descending stairs, sit-to-stand transfers (and vice versa) and general movements [9]. The exoskeleton devices are can be worn by those who are recovered from stroke [12] and physically weak [13]. Exoskeletons can be classified into full and partial lower limb exoskeletons. The distinguishing criterion is the number of human joints that a device runs parallel too. For example, a full lower limb exoskeleton contains joints located alongside the hip, knee, and ankle joints. Partial lower limb exoskeletons mostly focus on joints that work together with the knee or ankle joint [10].

(a) ALEX [14] (b) HAL [15] (c) Ekso GT [16]

Fig. 2: A few types of single lower limbs exoskeleton

As shown in Figure 2, few examples of powered lower limb exoskeletons which were designed and developed by other researchers. ALEX (Active Leg Exoskeleton) has developed from University of Delaware for used of stroke patients. The design of this exoskeleton comprises actuated hip and knee joint for the left leg as shown in Figure 2(a)[14] . The subject need to walk on a treadmill supported with display in front of them to provides visual reaction of the implemented gait trajectory [17]. ALEX is a motorized orthosis is design for gait rehabilitation of patients with walking disabilities to improve their walking gait. The system provides a walker with a connect on the trunk retains the subject stability during exercise.

HAL (Hybrid Assistive Limb) has been designed to improve and support the human motor functions. The project focus on providing walking motion support for stroke patient. Figure 2(b) shows, a first stroke patients demonstrate the improvement gait cycle with faster steps and longer stride [15]. As a result , the user can reduce the walking time because the HAL permits shift forward. Use of crutches to support the user for walking forward and body balance. Furthers, HAL developed the Robot Suit HAL (Hybrid Assistive Limb) to support user who suffered with SCI were it support voluntarily drive using a trigger based on patients bioelectrical signal [18].

Figure 2(c) shows the Ekso GT exoskeleton apply a human–computer interface based on motion, which exploits sensors, perceives actions made to determine intentions, and acts accordingly. It created by the American company in 2012. The user able to walk in a straight line, standing up from a sitting position and remaining raised for a long period of time. User can sitting down from a stand up position [16]. People who with hemiplegia due to a stroke, they can move independently from a wheelchair to a chair.

Spring Break Orthosis (SBO) is a hybrid exoskeleton which integrate Functional Electrical Stimulation (FES) into the system. SBO can eliminate dependency on the withdrawal reflex and the related complications of modification and poor control ability [19].

The effectiveness of the lower limb exoskeleton in supporting patients to control and restore their walking gait pattern depend greatly on the communication between motor actions and human limbs which require further research [20].

This paper focus on development of lower limbs exoskeleton control on two degrees of freedom, namely, hip flexion / extension motion and knee flexion / extension motion. The actuators used in this design is DC stepper motors selected based on torque, constant speed and weight.

2. Methodology

This section describes the methodology that was used in this research. Based on design exoskeleton by other researchers, the exoskeleton should be capable of human-robot interaction communication to increase the training effects [21]. Our primarily design idea was focused on safety precaution, interface weight compensation of the device and adaptability of the physical human-robot.

As shown in flowchart in Figure 3 this study started with the exoskeleton design used Computer-Aided Design software named AutoCAD. The anthropometric parameters of the human body are followed in exoskeleton design to make sure that the joints of exoskeleton are fitted with the user's joints [22]. The next step is hardware and material parameter selection according to the objective of this project design. The material was chosen based on the weight, strength and durability to provide more reliability of the exoskeleton [23].

Development or installation exoskeleton structure based on design including bag pack carrying the power supply and motor driver. The selected of appropriate stepper motor weight with enough torque including speed of rotation was chosen for the actuator of the exoskeleton. Stepper motor is used to extend and flexed the hip and knee during the gait cycle.

In design control system, microcontroller Arduino is used as are controller to control the movement of exoskeleton based on flexion and extension hip and knee angle in normal walking gait. Data from hip and knee exoskeleton are recorded to analyse the exoskeleton performance. Computer programming in control system can be updated as required by the user. The result of the experimental was produced for safety approval status under stroke rehabilitation guideline [24].

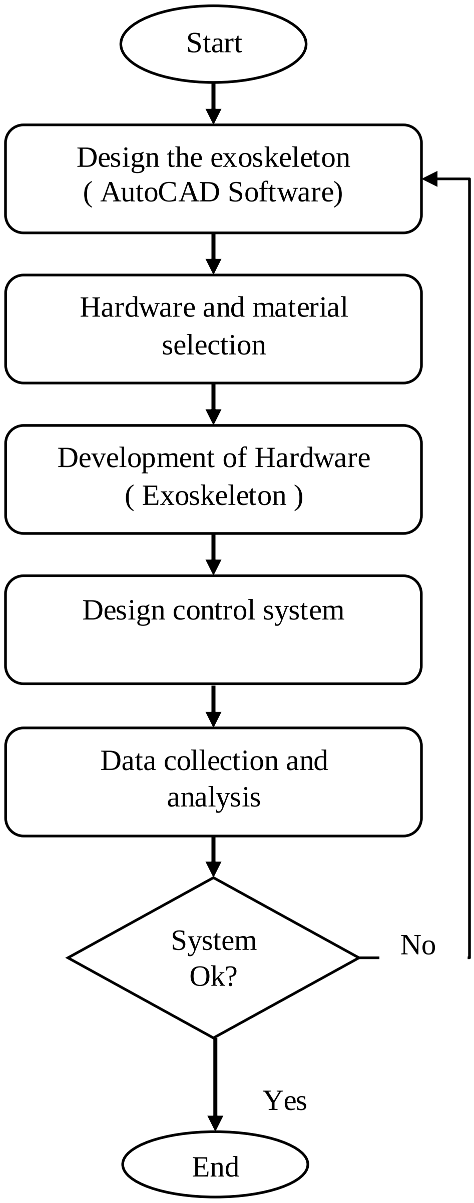

Fig. 3*:* Overview of product development methodology

2.1. Exoskeleton Platform

The lab scale exoskeleton is shown in Figure 4 was designed in mid-range specification for rehabilitation of adults between 1.60m to 1.70m height, with a maximum body weight of 65kg, with gait disabilities, such as stroke patients. It was conceived for assist-as-needed over ground gait training in a clinical environment, and to be used by patients who can stabilize their trunk while maintaining some level of balance. To avoid possible falls and injuries, patients should always be attended by clinicians, and safety devices may be necessary depending on the injury level additional such as crutches or wheel walker.

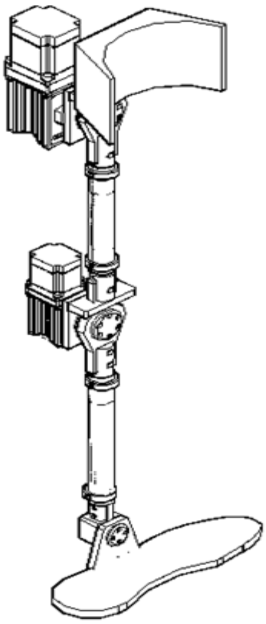

Fig. 4: Exoskeleton device schematic

This exoskeleton is conceived as a bilateral wearable device (about 12 kg) with two DoF (degrees of freedom), in which the hip and knee are powered joints. After considering the mechanical resistance and lightweight requirement, full aluminium is primarily used as the mechanical structure. Foam pads are used to minimize pressure against the skin and prevent damage. Leg exoskeleton are installed with two DC motors to help the movement of the hip and knee during the operation

2.2. Actuators

The design and selection of exoskeleton actuators are based on the typical identification of constant torque and high power of each joint during normal gait (not pathological) at lower speed. In this study, two DC stepper motors J86HB65-04 (for Hip) and J57HB56-03 (for Knee) are used to drive leg movement of the patient as shown in Figure 5. The stepper motor is known by its property to change a train of input pulses (typically square wave pulses) into an exactly defined increment in the shaft position. Each pulse moves the shaft through a fixed angle [25]. These motors are equipped with holding gear to avoid the exoskeleton device from loosening when out of power. This both joint motors will be driven with JB860M motor drivers.

Table 1 shows the specification of the J86HB65-04 and J57HB56-03 stepper motors. From the table, it shows the holding torque, rotor inertia and weight, which played important roles in the motor selection process to drive patient leg.

Figure 6 shows the control system block diagram controller for this study. This system utilized an Arduino to control the exoskeleton. This microcontroller was chosen for its ease to custom instruction, acceptable processing power and ability to run Arduino IDE based on C++ programming language. This device is also small, and relatively inexpensive compared to other platforms. The stepper motors, which acted as actuators for this system will drive the user leg for extension and flexion of hip and knee to perform the gait cycle. Angle data is collected laterally in process to validate the effectiveness of stepper motor.

Fig. 5: Stepper motor and driver [26]

Table 1: Stepper motor specification

Model	Step Angle (°)	Length L(mm)	Holding Torque (N.m)	Current (A/Phase)	Resistance (Ω)	Inductance (mH)	Rotor inertia ($g.cm^2$)	Weight (kg)	Shaft diamete (mm)
J86HB65-04	1.8	65	3.3	2.8	1.40	3.9	1000	1.7	9.50
J57HB56-03	1.8	56	0.9	3.0	0.75	1.1	300	0.7	6.35

2.3. Control Architecture

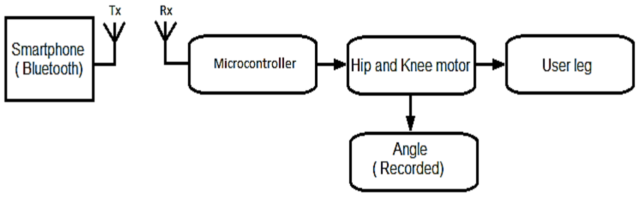

Fig. 6: Control system block diagram

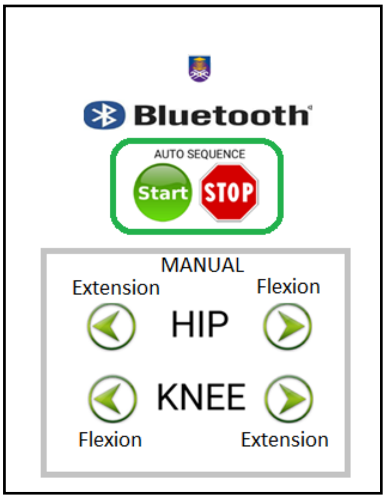

Fig. 7: Developed Android application to control exoskeleton

Figure 7 shows the screen interface on android phone for exoskeleton controller. The control input was performed by utilizing the smartphone device that make the developed android program for the user interface. The user interface was programmed in MIT app inventor and execute on an Android OS smartphone. It is basically an application that allows physiotherapist to control the execution of the gait cycle sequence during therapy session with the patient easily.

It communicates wirelessly using Bluetooth technology using Bluetooth HC-05 module [27]. The program will start when the "Bluetooth image" button is pressed to connect the device to the Arduino through Bluetooth. After the connection is established, the user can choose between auto or manual control the movement of exoskeleton.

Label "Auto sequence" part is where the two buttons are located. The 'Start' button is used to start the gait sequence. Both stepper motors will represent as actuators for this system to drove the exoskeleton for extension and deflexion of hip and knee to perform the gait cycle. The degree of motor angles has been program based on normal gait cycle. The gait cycle will continue until the 'STOP' button is pressed to stop the gait sequence.

The user also can select "Manual" sequence to drive extension or flexion for hip or knee motor manually. The manual sequence features were installed for the physiotherapist or patient to perform hip and knee extension or flexion according to their needs or requirements. Manual button also can be used to set the exoskeleton back into its initial position.

The 'Hip' button is used to drive the hip motor where the button on the left and right to of each side will drive the respective hip. The motor will rotate when the button is continuously pressed and stop after the button is released.

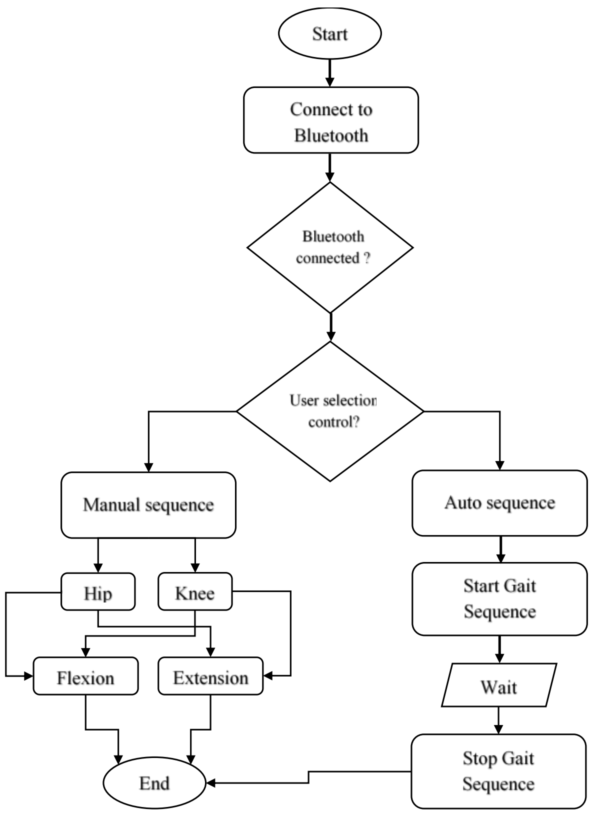

Fig. 8: Flowchart in android controlled device

Figure 8 shows the flowchart working system developed to control the exoskeleton. After the system is connected via Bluetooth, the system ready to perform manual or auto sequence based on selection by the user. In manual sequence features, hip and knee can be controlled separately for flexion or extension movements as user required. This button also can be used to revert the position of exoskeleton to preliminary condition.

Auto sequence features is used to start exoskeleton to move as human walking gait. The degree of both motor rotation as been program in microcontroller according to human gait cycle phases as Table 3. The gait sequence will remain activate until the microcontroller received stop instruction.

2.4. Data Collection

For this study, six volunteers with no history of lower extremity injuries are taken. All participants are students from Universiti Teknologi Mara (UiTM), between the age of 25 to 44.

The estimated of leg weight and height has been carried out using anthropometric data. Anthropometry data is a branch of anthropology concerned with comparative measurements of the human body and its parts, as well as the variables which impact these measurements based on work by Winter's [22] . This data is used in human factors or ergonomics applications to ensure that design and standards are realistic.

Table 2: The Anthropometric equations

Leg	Equation of length	Equation of weight
Thigh	0.433H	0.1000M
Shank	0.433H	0.0465M

Table 2 provides the Anthropometric equations to calculate human thigh and shank of every subject, where H is the subject's height in meter (m) and M is the subject's total weight in kilogram (kg).

The outline of data collection procedure conducted as followed. First, the subject's height and weight are measured using the scale. Then, the subject is equipped with the exoskeleton device. After auto sequence button is pressed, the subject will start moving until five steps forward as shows in Figure 9 before the button stop will be pressed to stop the sequence. Each of motor is attached a potentiometer to record the angle of hip and knee during extension and flexion throughout the experiments.

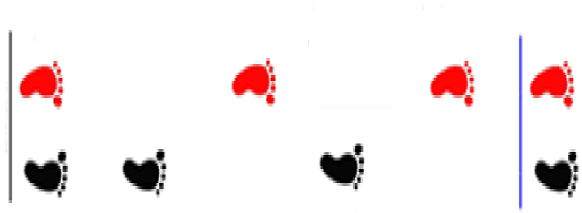

Fig. 9: Steps procedure by the subject during data collection

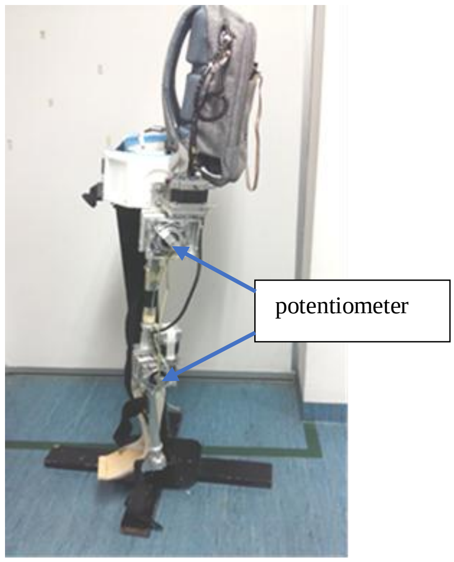

Fig. 10*:* Developed lower limb exoskeleton device

Figure 10 present an overview the fully developed lower limb exoskeleton device. The backpack is used to store the motor driver and power supply, which required 24V and 8A to power up. The patients will wear the backpack when walking for the convenience purpose.

2.5. Sequence Development

Normal gait cycle from Bovi et al [28] is used as reference to compare with the data collected from six subjects. The data of the hip and knee angle during gait cycle was collected, analysed and divided into eight different gait cycle phases as shown in Figure 1.

Table 3: The hip and knee angle for one gait cycle

	Gait phases	Mid-stance	Terminal stance	Pre-swing	Toe-off	Mid-swing	Terminal swing	Heel strike	Loading response
Exo. Gait	HIP ANGLE	0˚	-30˚	0˚	15˚	30˚	30˚	30˚	0˚
	KNEE ANGLE	0˚	0˚	65˚	45˚	20˚	0˚	15˚	0˚

Tabulated angle data in Table 3 represent the exoskeleton gait phase and the maximum angle for hip and knee respectively. The hip and knee angle data are integrated with the exoskeleton device programming in microcontroller to determine the output sequence of the exoskeleton for one gait cycle.

The installed programmed in microcontroller start with mid-stance phase were both angle at zero degree as initial gait phase. The hip motor starts to extend until minus thirty degree and the knee remain at zero degree until hip enter the trailing position in terminal stance. Knee and hip motor flexion together, it prepared to leave the ground. At pre-swing phase knee motor angle at sixty-five degree and hip motor flexion from minus thirty degree to fifteen degree, at this moment the load through the exoskeleton decreases. Throughout exoskeleton at toe-off position, the only area of another foot is on the ground. The swing phases starts when the exoskeleton is lifted off the floor.

At mid-swing event, the hip flexion brings the leg exoskeleton forward in front of the body weight line. The knee motor can extend to zero degree in preparation for another leg heel to touch the floor at terminal swing phase. Next phase represents the exoskeleton enter the heel strike phase, when the AFO heel of the exoskeleton touched the ground in the first sequence of stance phase. The last event is the loading response, where the body weight is transferred from another leg into leg exoskeleton with the AFO foot flat on the ground. The process sequence will start again until the program received the stop instruction from the user.

3. Result and Discussion

In this section, results from the six subjects will be discussed. All subjects were tested by allowing them to walk in five steps (see Figure 9) using lower limb exoskeleton.

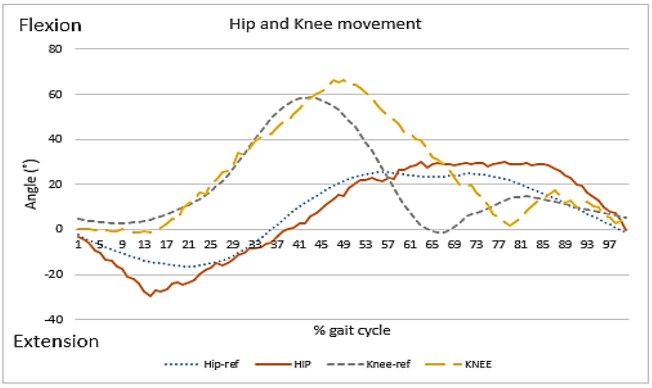

Fig. 11: Data from one subject at one gait cycle.

Figure 11 shows comparison data of hip and knee angle to the normal hip and knee angle for one subject at one full gait cycle. The graph shown noise in the data appeared because of the vibration from the stepper motors during the measurement. The potentiometer used to measure the hip and knee angle movement was installed directly to the stepper motor's outer rotor, resulting directly disturb to the potentiometer reading.

The average data angle of hip movements against from the six subjects for one full gait cycles (point P1-P8) is presented in Figure 12. The result is compared to an adult normal walking gait phases (point Q1-Q8) as recorded by Bovi et al [28]. From the graph, it shows the comprehend that the hip angle for flexion and extension is not much different except for terminal stance, mid-swing, terminal swing and heel strike. The different is due to extended angle on exo. gait- hip angle (P2, P5-P7) and hip motor must carry thigh and shank frame including knee motor. Overall, hip leg exoskeleton angle is delay by 11% gait cycle compared to normal hip gait angle.

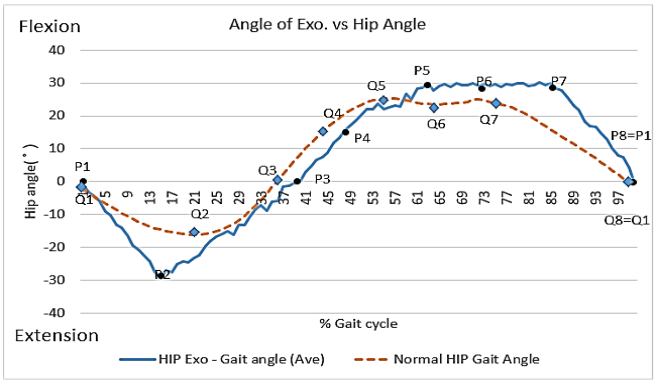

Fig. 12: Hip movement average of six subjects

Table 4: Distributed points on gait phases for hip

	Gait phases	Mid-stance	Terminal stance	Pre-swing	Toe-off	Mid-swing	Terminal swing	Heel strike	Loading response
Normal gait		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
	HIP ANGLE	0˚	-15˚	0˚	15˚	25˚	23˚	25˚	0˚
Exo. Gait		P1	P2	P3	P4	P5	P6	P7	P8
	HIP ANGLE	0˚	-30˚	0˚	15˚	30˚	30˚	30˚	0˚

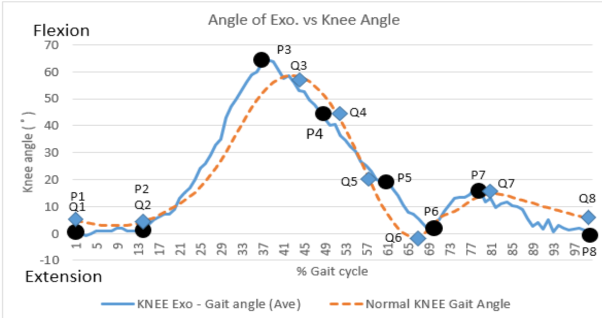

Fig. 13: Average of knee movement of six subjects

Table 5: Distributed points on gait phases for knee

	Gait phases	Mid-stance	Terminal stance	Pre-swing	Toe-off	Mid-swing	Terminal swing	Heel strike	Loading response
Normal gait		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
	KNEE ANGLE	5˚	5˚	60˚	45˚	20˚	-5˚	15˚	5˚
Exo. Gait		P1	P2	P3	P4	P5	P6	P7	P8
	KNEE ANGLE	0˚	0˚	65˚	45˚	20˚	0˚	15˚	0˚

Figure 13 shows the average data of knee movements angle (point P1-P8) from six subjects. The result is compared to an adult normal gait cycle (point Q1-Q8) as documented by Bovi et al. From the graph, the angle of knee flexion during gait cycle stay close to the input value reference of the gait cycle sequence except at pre-swing phase (P3) as shows in Table 5. The extended flexion angle at pre-swing is required to make AFO foot clearance during swing phase. Knee motor with constant torque will flexion from mid-stance to loading response. From the graph, knee can flexion up to sixty-five degree according to angle has been installed.

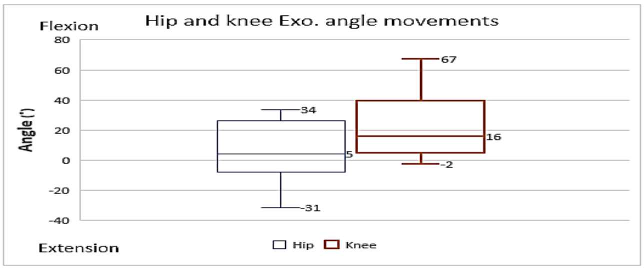

Fig. 14: Boxplot of hip and knee exo. angle movement

Figure 14 shows the box plot of hip and knee exoskeleton angle movement between six subjects for five steps. From the graph, it shows maximum average hip angle movements for six subjects are between thirty-four degree for flexion and minus thirty-one degree for extension, which nearly followed the intended angle output from microcontroller. Average knee angle for similar six subjects are between sixty-seven degree for flexion and minus two degree for extension, which it closely to angle has been program in microcontroller. Median value represents of standing position before the user start the gait cycle. The average value for hip is five degree and knee are sixteen degree, however the user needs the elbow crutches to support their balance during walking and to avoid falls.

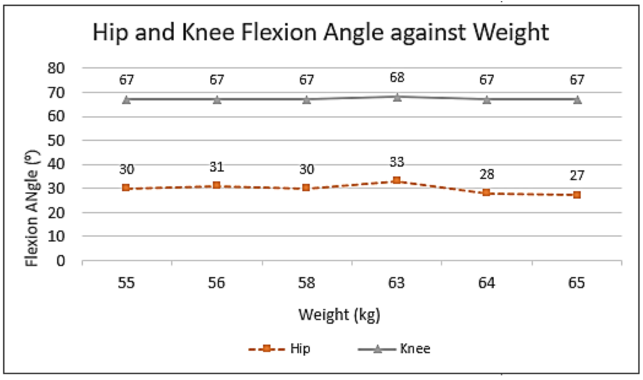

Fig. 15: Maximum hip and knee angle flexion against weight

The Figure 15 shows maximum angle of hip and knee flexion against weight for six different subjects. From the graph, it shown the stepper motor is enough torque to work properly for subject below 64kg. While knee motor, shows that the maximum flexion angle is nearly the same which is sixty-seven degree. It shows that, stepper motor has enough torque for knee lifting process in the gait cycle for all subjects.

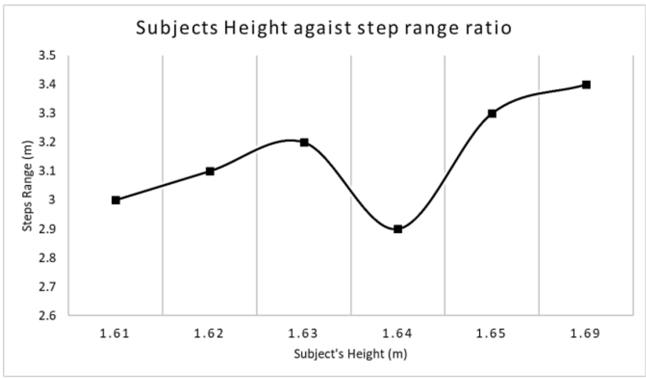

Fig. 16: Subject's height against walking distance

Figure 16 shows the subjects' height against walking distance when using the developed exoskeleton. The subjects were instructed to walk in five steps forward and stop. From the observation, the subject height will result in more walking distance. However, there is one odd result due to the subject's walking pattern.

As focus on safety precaution, in this project two stepper motor attached with worm reducer gear are used to prevent and hold patients from fall incident if the supply is weak. Circuit protection and isolation are build-in in power supply module to avoid patients form short circuit or electrical shock if occur. Emergency push button is also used to cutoff power supply if needed. In developing this exoskeleton, aluminium is used in the mechanical structure in deliberation of mechanical resistance and light weight. The thigh and shank parts are equipped with velcro straps to secured exoskeleton firmly on user without effect the user skin.

4. Conclusion

In this research, the lower limb exoskeleton device has been developed to be used by stroke survivor. Its content controller system, electrical motor system, power supply system and mechanical system. In controller system, some control strategy is programmed in microcontroller according to the normal gait phases. Electrical motor system included a motor driver and DC power supply. The mechanical design system is a lower limb framework and stepper motor. The experiment was carried out with six normal subjects wearing the exoskeleton in auto-sequence mode shows that it can generate a gait cycle pattern identical to normal gait cycle. The data collection results show that the lower limb exoskeleton is achievable and effective for the lower limb rehabilitation method for stroke patient.

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