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MECHANICAL ANALYSIS OF WEARABLE LOWER LIMB EXOSKELETON FOR REHABILITATION

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Abstract

This paper presents the mechanical analysis of a lower limb exoskeleton for rehabilitation for both legs that was developed in University Putra Malaysia (UPM). The main objective of the project is to develop a wearable exoskeleton system based on the average height of Malaysian to enhance the wearability of the system to lower limbs. An anthropomorphic design was adopted in the prototype with pneumatic actuations at the knee with one (1) degree of freedom (DOF), and ankle joints with two (2) DOFs via McKibben Pneumatic Artificial Muscle (MPAM). The prototype also mimics normal human joints range of motion (ROM) to enable movements similar to normal human gait patterns. Such anthropomorphic prototype was designed to fit users with different heights for both genders (male: 1.6-1.8 m, female: 1.5-1.7 m). As a result, the frame can be adjusted from 0.37-0.42 m for thigh segment and 0.385-0.445 m for lower leg segment. The actuation properties of MPAM also determined as well as Vertical Ground Reaction Force (VGRF) analysis to be performed to determine the performance of the prototype once integrated with actuation system and control system.

Keywords: Mechanical analysis, Lower limb exoskeleton, Anthropomorphic design, Pneumatic actuation.

1. Introduction

Locomotion training is used to assist patient of neurological diseases to improve their walking ability and have been proven to be a highly effective approach [1-3]. Locomotion training could be used to provoke motor plasticity, the ability of central nervous system to change and adapt to the required alternative pathways

Nomenclatures

v	Length of respective part of prototype, m
w	Length of respective part of prototype, m
x	Length of muscle, m
y	Length of respective part of prototype, m
z	Length of muscle, m

Greek Symbols

θ	inclination angle of knee joint, degree

Abbreviations

DOF	Degree of freedom
MPAM	McKibben pneumatic artificial muscle
ROM	Range of motion
VGRF	Vertical ground reaction force

for sensory perception or motor skills [4]. Applications of rehabilitation robotics in rehabilitation plan have increased the efficiency of rehabilitation and decrease the workload of physiotherapist. The rehabilitation robotics allows more intensive repetitive motions training and reduces dependency towards therapist during the rehabilitation process. This paper presents the mechanical analysis of a lower limb exoskeleton prototype for rehabilitation that was constructed in Universiti Putra Malaysia (UPM). According to [5], an exoskeleton in man-machine intelligent system is defined as a system that combines human intelligence and machine power. Main objective of the project is to build a wearable exoskeleton system based on the average height of Malaysian to enhance the wearability of the system to lower limbs. The prototype is designed anthropomorphically, with adjustable attachments at thigh and lower legs, and powered actuation at knee and ankle joints.

2. Actuation System

Pneumatic actuation is chosen as the main actuation system in this prototype. Compressed air is used to power the actuators that generate desired movement. Compared to electro-motor actuation system, the mobility of the system is lower as the air compressor and air tank are compulsory elements of pneumatic actuation system. Moreover, the system is used for rehabilitation purpose; patients will only be locomote on treadmill. Therefore, remotely tube connected compressed air tank could be placed within vicinity of the testing venue.

Compared to various pneumatic actuators, McKibben Pneumatic Artificial Muscle (MPAM) as shown in Fig. 1 was selected. MPAM is widely utilised in such system as depicted in [6]. MPAM is constructed of an inner tube surrounded by nylon braided sleeve. Both end of inner tube and sleeving are connected to custom-design fittings that serve as compressed air closure and to transfer force generated to the system.

Fig. 1. McKibben Pneumatic Artificial Muscle.

2.1. Actuator selection

Various considerations have been made in the selection of actuators for this project. MPAM was chosen due to the following considerations. According to [6], the operation of MPAM is very similar to actual human muscle. Similar to human muscle, pulling force are generated by MPAM during contraction as the compressed air is channeled into MPAM and elastic force are generated during the relaxation.

Secondly, the MPAM generate high power and force to weight/volume ratio. As the prototype will be used by patient for locomotion training, weight is one of the major factors considered in the design process of the prototype. In addition, ease of fabrication and ease for replacement of MPAM were also considered in the selection of actuator for the prototype. Lastly, MPAM is capable of generating soft contact forces due to its elastic properties, which is safe to be implemented in a man-machine system such as this prototype.

2.2. Antagonistic setup

Due to the single-acting properties of MPAM, the antagonist configuration is used to generate bidirectional rotation at respective joints. In this setup, two MPAM are used for the actuation of one joint. During the operation, one of the MPAM is used to move the load while the other is used to generate the braking force and vice versa. Besides that, the braking force generated by the MPAM could be used as a safety mechanism whereby the maximum length is fixed. Figure 2 shows the antagonist MPAM setup of the prototype.

Fig. 2. Antagonist Configuration of MPAM.

2.3. Optimum length of MPAM

To determine the optimum length of MPAM, experiments and quantitative analysis are carried out. Two experiments were conducted. The first experiments were to determine the maximum allowable load of the MPAM, whilst the second experiment looked into the differences in contraction length for various setting of MPAM mounted in different position. The pneumatic circuit connections and experimental setup are shown in Fig. 3. An air compressor is connected to the MPAM via pressure regulator with filter. The MPAM is hanged with the load pulling downward for the testing of maximum allowable load experiments.

Fig. 3. Connection of MPAM and Experiment Setup.

The relationship between inclination angle of each joint and respective MPAMs can be expressed in a trigonometric formula as shown in Fig. 4. Implementing these formulas, the contraction of each muscle required to generate desired movement in each joint could be modelled with ease. To depict the relationship between knee flexion muscle length, x and knee joint, θ, the formula is expressed as the following:

$$\theta = 180° - tan^{-1}\frac{w}{v} - cos^{-1}\frac{v^2+w^2+y^2+z^2-x^2}{2(v^2+w^2)(y^2+z^2)} \qquad (1)$$

where w, v, y are the lengths of respective parts (m), x and z are lengths of muscle (m) and θ is the inclination angle of knee joint (degree).

Figure 5 depicts the mathematical model of the ankle joint to determine the relationship between the dorsiflexion and plantar flexion muscle. The relationship between length of dorsiflexion muscle, x, length of plantar flexion muscle, z and ankle joint, θ, can be expressed with the following mathematical expression:

$$\Delta x = - \Delta z \qquad (2)$$

$$\theta = 90° - tan\frac{w}{v} - cos^{-1}(\frac{x^2+y^2-w^2-v^2}{2xy}) \qquad (3)$$

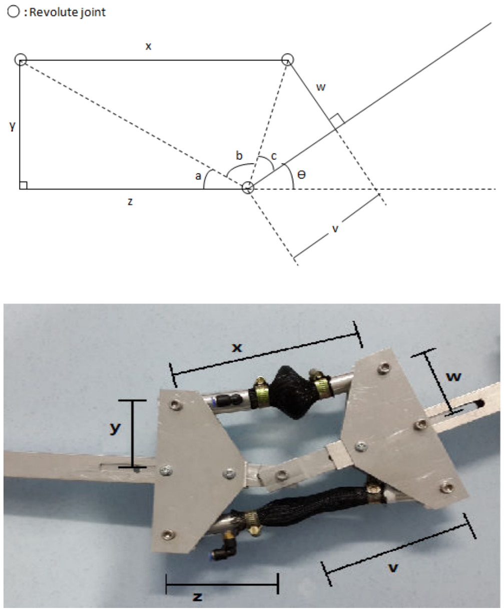

Fig. 4. Mathematical Model of Knee Joint.

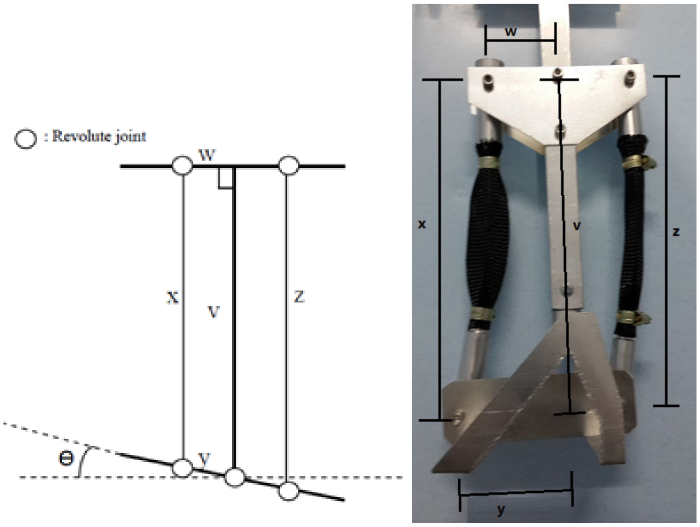

Fig. 5. Mathematical Model of Ankle Joint.

3. Mechanical Design

To cater for differing user anthropometric, the system has included the adjustable limb attachments. Table 1 shows the anthropometric data of lower limb segment length for both genders [7]. Table 2 shows the segment length of thigh and lower leg for male (height: 1.6-1.8 m) and female (height: 1.5-1.7 m).

Table 1. Anthropometric Data of Thigh and Lower Leg.

Segments	Male	Female
Thigh	23.2	24.9
Lower leg	24.7	25.7

Segments lengths expressed in percentages of total body heights

Table 2. Segment Length for Male (height: 1.6-1.8 m) and Female (height: 1.5-1.7 m).

Segments	Male (m)	Female (m)
Thigh	0.370-0.420	0.370-0.420
Lower leg	0.395-0.445	0.385-0.435

Elements of safety are also incorporated in the design whereby the maximum and minimum movement limits of the prototype are in accordance to normal human biomechanics. The inner part of a knee joint is design as a quarter circles to allow only 90° of flexion, whereas mechanical stoppers are used to limit degree of freedom ankle joint. Also, the braking MPAMs are also act as the mechanical stopper.

4. Results and Discussion

The properties of MPAM were determined and calculation was done to determine the best configuration of MPAM. The prototype was fabricated according to the design and the ROM of each joint are determined and match the design. The length of the adjustable frame can be adjusted from 0.37-0.42 m for thigh segment and 0.385-0.445 m for lower leg segment. The frames are shown in Fig. 6.

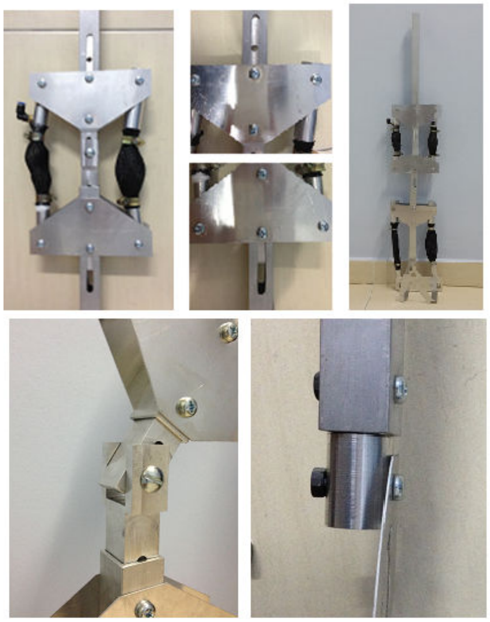

Fig. 6. Frames of the Prototype.

4.1. MPAM

The mechanical properties of the MPAM were tested using 60 *psi* (413.7 *kPa*) of compressed air. It is observed that the muscles were able to sustain up to 14 kg of external loading. Figure 7 shows the result obtained from the experiments. From the graph, we notice that the MPAM has a minimum length of 0.12 m until the load increase from 7 kg to 8 kg. The length of the MPAM is 0.125 m for load of 8 kg to 11 kg, and 0.13 m for 12 kg of load. The MPAM failed at 14 kg of load due to the detachment of the inner tube and sleeve from the fitting. Furthermore, the differences in contraction length under various setting were also tested and shown in Fig. 8. From the calculation and experiment data we collected, the optimum length of MPAM for the knee joint is 0.26 m.

4.2. Prototype

The prototype would fit male users with the height within 1.6 to 1.8 m and female users within the height range of 1.5 to 1.7 m. The allowable range of motions for joints was measured. The ROM of the knee joint is 0 to 90° of flexion/extension whereas for ankle joint of two DOFs with -15 to 10º for dorsiflexion/plantar-flexion, and -5 to 5º inversion/eversion under non-actuated conditions. It is observed that the ROM of each joints have allowed the user to perform normal walking pattern within the safety range.

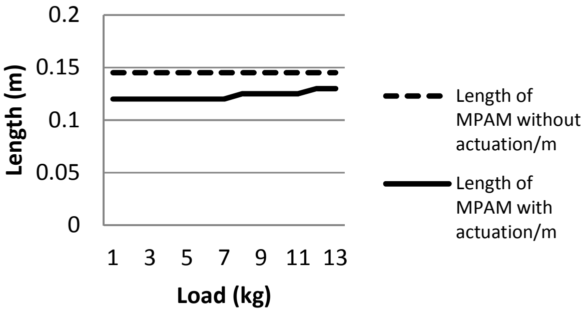

Fig. 7. Result of MPAM Load Test.

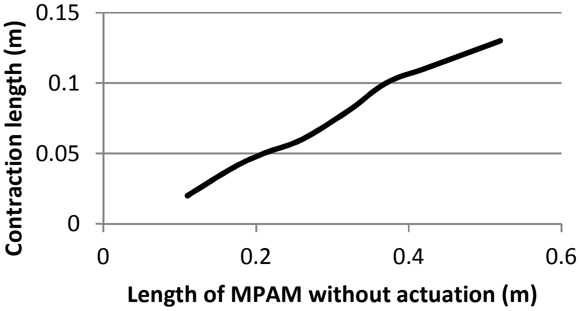

Fig. 8. Result of MPAM Contraction Length Test.

5. Conclusions

McKibben pneumatic artificial muscle is chosen among various pneumatic artificial muscles and tested. The best configuration of MPAM was found through both experimental and theoretical techniques. A lower limb exoskeleton prototype for rehabilitation for both legs was developed.

The frames of the prototype allows user to perform normal walking gait within the normal range of motion. To further determine the performance of the prototype, the actuation system and control system will be integrated and analyse by VGRF analysis. With the data collected from VGRF analysis, determinations of walking gait including stability are possible.

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