

Continuous Progressive Actuator Robot for Hand Rehabilitation

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Abstract—This paper presents the development of a soft rehabilitation robot to conduct Continuous Passive Motion (CPM) for hand rehabilitation. The main contribution of this work is the implementation of a McKibben actuator as an artificial muscle due to its proven advantages: simple structure, light weight, and high power-to-weight ratio. The development worked successfully when tested on a healthy subject, where the flexion and extension of the finger were controlled with an antagonistic pair of actuators. However, there is a limitation of the McKibben actuator regarding its length-dependency. In this research, the concept of a pulley system was proposed to overcome this limitation. Although there is a friction factor that reduces the contracting displacement by at least 15% of the original displacement, a pulley is still a potential solution as it can reduce the installation space of the actuator from 40 to 15cm while still producing sufficient force for the finger motion. Throughout this research, it was found that the pattern of the flexor pulley system is affecting the system's efficiency in terms of motion assistance.

Keywords—McKibben actuator; Continuous Passive Motion; finger exoskeleton; hand rehabilitation

I. INTRODUCTION AND BACKGROUND

According to the National Stroke Association of Malaysia (NASAM), stroke is the third leading cause of mortality in Malaysia, after heart disease and cancer [1]. An estimated 0.14% of the population (40,000) of Malaysians succumb to stroke each year. Stroke is a type of brain injury, it can strike anyone, at any time and at any age [2]. Stroke affects its sufferers in different ways, depending on the location and extension of the damage in the brain. Most of the stroke patients suffer from hemiplegia, which is the loss of movement on one side of the body [1]. This leads to difficulties in many activities as most daily tasks can hardly be done without using both hands. Hence, rehabilitation is a crucial step to help stroke patients to regain their capability in order to manage their daily

activities. Rehabilitation is usually conducted when the patient is still in acute care in order to prevent additional stroke and stiffness at the affected joint. The rehabilitation that is practiced in the early phase post-stroke patient is known as Continuous Passive Motion (CPM). CPM provides regular movement to a particular joint for rehabilitation without patient's muscles being used [3]. CPM is claimed to bring beneficial effects especially on gaining a range of motion. However, there are some disadvantages of conventional rehabilitation. Conventional rehabilitation has to be either conducted with the help of a professional physiotherapist or monitored in hospital/nursing facilities [2]. As the number of stroke patients in Malaysia increases year by year, there is a lack of physiotherapists in rehabilitation centers. In addition, current rehabilitation is subjective and not reliable as it is based on manual visual evaluation and there is no data collection [4]. There is no analytical data to evaluate the recovery progress of the stroke patients systematically.

One alternative of conventional rehabilitation is rehabilitation robotics. It helps in reducing the dependency on manual labor and enables data collection. However, there are some drawbacks on current rehabilitation robotics. Rehabilitation robots can be divided into two main types based on their actuators, which are electrical motors and soft actuators. Electrical motors are heavy, bulky and difficult for the patients to wear by themselves. The rigid frame is putting the patients in an uncomfortable situation and it is quite dangerous when an accident occurs. For example, the Hand-Assist Robot [5], is designed with 18 Degrees of Freedom (DOF) consisting of four finger motion assist mechanisms, a thumb motion assist mechanism and a wrist motion assist mechanism. It is driven by 22 servo motors that give limited flexibility and portability to the wearer. HEXOSYS [6] is designed with a linkage mechanism for thumb and index finger to conduct continuous finger flexion and extension. However, the users have to wear the system that weighs 1kg on their hand. The system was

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improved and HEXOSYS II [7] was developed that weighs 600gr. Assist On-Finger has a lightweight frame that is adjustable to the users' phalanges length but is still rigid and complex. The MRI compatible finger rehabilitation robot [9] operates using an ultrasonic motor. This motor will have a rise in temperature when operating for a long period of time. Therefore, it is designed so that the motor is located in a distance from the hand exoskeleton to ensure the safety of the user. 3D printed myoelectric robotic exoskeleton [10] was developed as a low-cost and lightweight finger exoskeleton. It is easy to fabricate but looks space consuming and fragile. Meanwhile, the hand rehabilitation exoskeleton [11] that was designed to fit fingers of different thicknesses was constructed of gear and slider and would be worn on top of dorsal of the subject's hand. Another soft bending actuator for finger flexion was proposed by authors in [12], which developed a 3-D finite-element analysis of fiber-reinforced actuator.

Conventional actuators mainly consist of electrical motors widely used in robotics the past decades, add excessive weight to robots. Additionally, the rigid structure of the motor limits the application in some situations that require flexibility. Hence, soft robotics technology emerged and became a popular research field. Soft actuator refers to a device that transforms the power from the power source to mechanical power through the deformation of its materials in a particular structure [13]. Soft actuator is being applied in various fields, mostly in biomimicry and medical applications. Some soft actuators are bending pneumatic rubber actuator [14], P-ELSA [15], Ecoflex [16], McKibben soft actuator, etc. McKibben soft actuator was introduced in 1958 but was popularized at the beginning of the 1960s [17]. It is composed of a rubber inner tube and surrounded by a double-helix braided sleeve [17]. When it is pressurized, the inner tube will expand and the orientation of the braided sleeve will cause the actuator to contract, generating a pulling force [18]. This characteristic is very similar to muscles' behavior, since the muscle will grow in width and shrink in length during contraction [19]. Besides, it has high power-to-weight ratio compared to motors due to its simple structure and light weight [20]. It is also easy to be maintained and has a comparatively lower cost than other hard actuators. It does not produce heat except for friction, thus the risk of accidental fire is low. The elastic inner tube is also stretchable allowing it to be stretched when a greater opposing force acts on it. It promotes a safer interaction, so that it would not force human motion, something that could lead to severe injuries. Therefore, this paper focuses on the implementation of the McKibben soft actuator as a pneumatic artificial muscle for the rehabilitation robot that conducts hand motion required for CPM. This information and capability could be distributed in the society and for e-health communication purposes [21].

II. SYSTEM DESIGN

The system consists of two soft actuators that are connected in antagonistic pairs for each finger. It has a 24V operating voltage and 0.3MPa operating pressure. The pressure can be controlled and supplied to the system by using an analog regulator based on the programmed procedure for CPM. When the patients are given a task such as grabbing an object, the system will obtain the finger bending data from the flex sensors

attached on top of each finger. The data collected will then be visualized as a data that can be used for recovery progress tracking. The finger exoskeleton is designed to mimic the flexor pulley system of human finger. Dyneema rope is used as a tendon to pull the finger as it offers better strength to weight ratio. It is fixed on a few points on the gloves based on the location of ligaments in human fingers. The attachment of Dyneema rope on gloves for the exoskeleton prototype is shown in Figure 1. The pattern of the flexor pulley system used on the finger exoskeleton will affect its functionality. Hence, several patterns were tested and compared to find the most suitable pattern. Since the actuator works as an artificial muscle producing pulling force when it contracts, the end of the actuator needs to be fixed. The actuators that function for the extension of the fingers are fixed at the elbow by using elbow guard while the actuators that function for the flexion of the fingers are fixed at the shoulder by using shoulder support as shown in Figure 1. Both the elbow guard and shoulder support are easy to wear as they only need to be fastened using Velcro fastener.



Fig. 1. Prototype exoskeleton with attached Dyneema fibre ongloves

III. RESULTS AND ANALYSIS

A. Overall System

The system is programmed with the repetitive exercise that is required for rehabilitation. The exercise focuses on the flexion and extension motion of the human finger and each finger is controlled by an antagonistic pair of McKibben actuators. One of the pair of actuators will contract to control the flexion motion while another actuator will control the extension motion as shown in Figure 2. The CPM exercise includes either moving 5 fingers together or finger by finger movement. It can also be programmed to have a full flexion or partial flexion as shown in Figure 3 as it is controlled by analog valves. These functions help the patients' brain to relearn the lost skills of moving their hands.

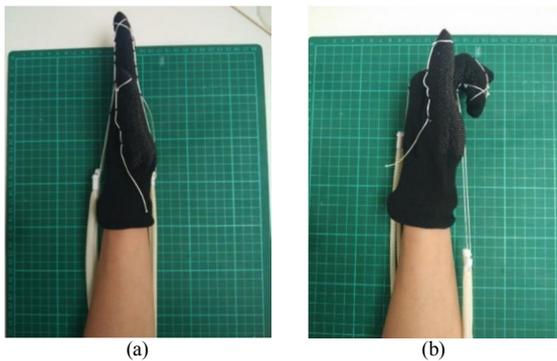


Fig. 2. Programmed CPM exercise

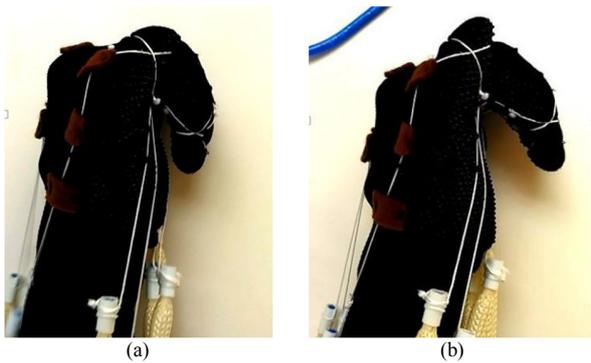


Fig. 3. Analog control of CPM: (a) Full extension (analogue:255), (b) partial flexion (analogue:200)

B. Flexor Pulley System

When conducting CPM, the bending of the fingers was influenced by different types of flexor pulley system.

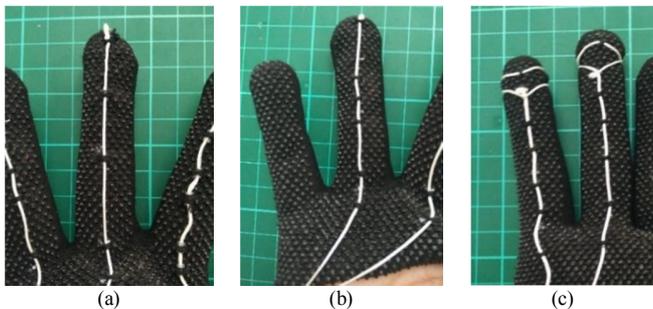


Fig. 4. Pattern of the flexor pulley system for flexion

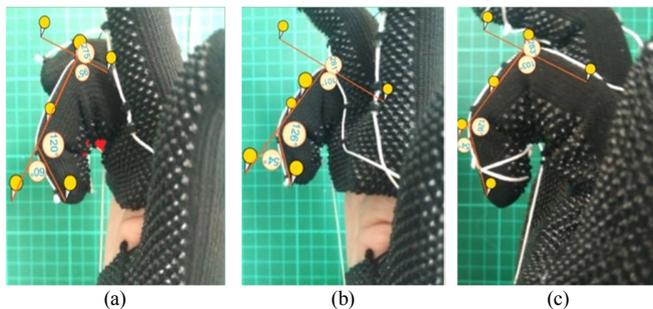


Fig. 5. Results from the pattern of the flexor pulley system for flexion

As the flexor pulley system of finger exoskeleton is different with the flexor pulley system embedded inside human fingers, they cannot be exactly the same. Therefore, different pulley systems were tested to obtain the most suitable design. Each pattern of flexor pulley system is shown in Figures 4 and 5 for flexion and extension respectively.

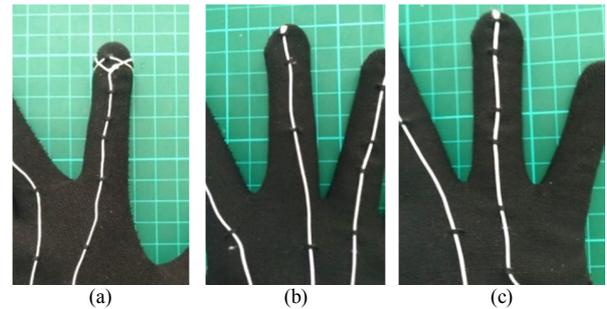


Fig. 6. Pattern of the flexor pulley system for extension

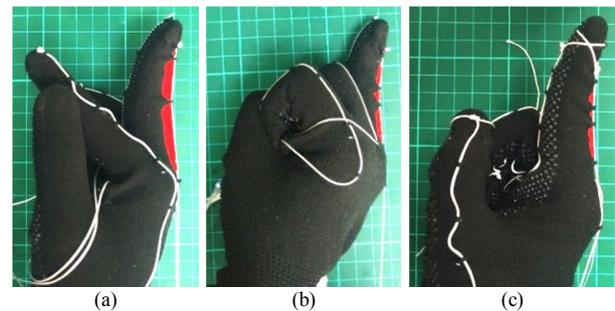


Fig. 7. Results from the pattern of the flexor pulley system for extension

C. Space Optimization for Actuator Installation

The McKibben soft actuator has a contraction ratio of 20% when supplied with 0.3MPa pressure. This becomes its weakness as it makes the design length dependent and not space-effective. This issue is worsening when used in this application where its functionality will be affected by arm bending. Therefore, a double groove pulley system is proposed to optimize the space consumption for the installation of the actuator. Some experiments were conducted to examine how the pulley system affects the contraction of McKibben soft actuator. The double groove pulley is designed with different circumference on each groove as shown in Figure 8. It works similar to the concept of gear. The McKibben actuator would connect to the groove with smaller circumference while the other groove would be connected to the load. The relation between the circumference of both grooves can be presented as pulley groove ratio as in (1). When McKibben muscle contracts and rotates the pulley by one rotation, the greater circumference on the other groove will amplify the contraction.

$$r_p = \frac{\pi d_L}{\pi d_M} \quad (1)$$

$$L_L = L_M r_p \quad (2)$$

where r_p =pulley groove ratio, d_L =load groove diameter, d_M =McKibben groove diameter, L_L =contraction length on load, and L_M = contraction length from McKibben.

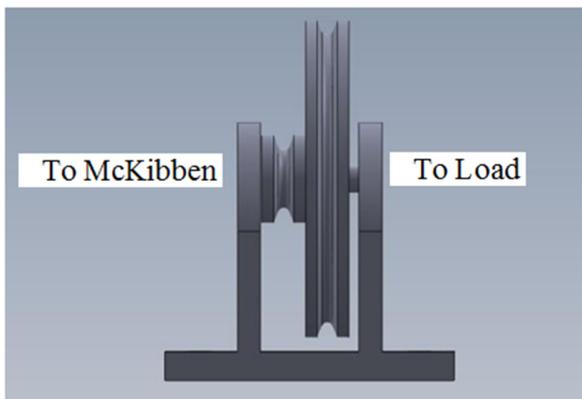


Fig. 8. Double groove pulley

Some experiments were conducted to analyze the effects of double groove pulley towards the contraction ratio of McKibben muscles and the results are shown in Figure 9. The

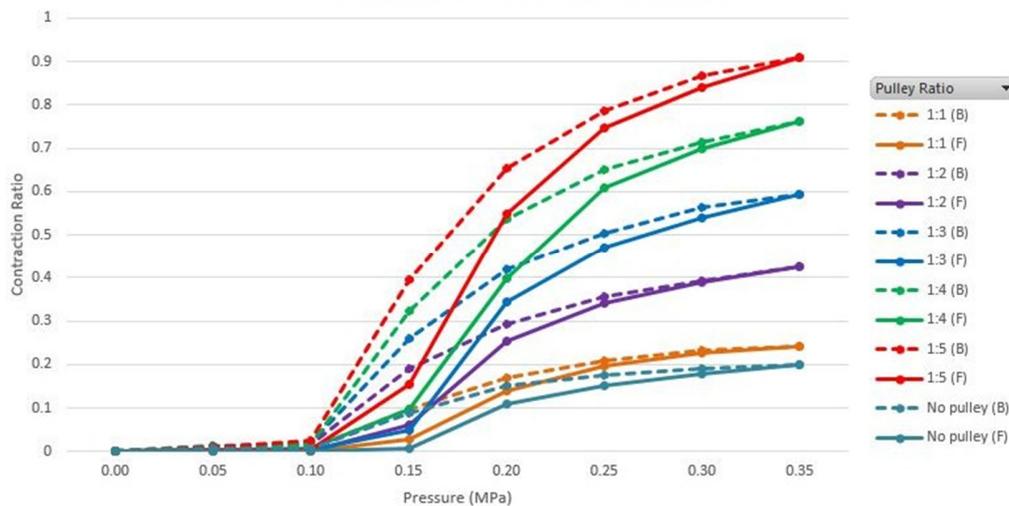


Fig. 9. Effects of pulley groove ratio towards the McKibben contraction ratio of McKibben

IV. CONCLUSIONS

In this work, a wearable robot was developed to carry out repetitive exercises with soft structure which is comfortable and safe for stroke patients. McKibben soft actuators were used as artificial muscles of the hand exoskeleton. The device contains two modes, one conducting CPM while the other mode keeps track of the patients’ recovery progress. The most suitable flexor pulley system for this finger exoskeleton was determined. A solution by making use of a pulley system to optimize space consumption was introduced. It was proved theoretically and experimentally that the mechanism decreases the installation space and increases the extension effectively. The experiment showed the force applied by McKibben soft actuator is sufficient for the flexion finger motion of both robotic and human hands. However, further considerations need to be concerned for improving the system. The fabric glove is not a good option for the

operating voltage is 24V DC with the supplied air pressure of 0.4MPa. The results show that the contraction ratio can be improved with the aid of the double groove pulley. The greater the pulley groove ratio, the greater the improvement of the contraction ratio. The experimental contraction ratio is compared with the calculated contraction ratio in Table I. For 1:1 pulley, the contraction ratio should be the same as without pulley, but the experimental contraction ratio is slightly higher. This is because the diameter of the load pulley groove will increase when the rope is rolled up into the pulley, hence further increase the pulley groove ratio.

TABLE I. CALCULATED AND EXPERIMENTAL CONTRACTION RATIO

Pulley groove ratio	Calculation	Experiment
1:1	0.1985	0.2424
1:2	0.3970	0.4242
1:3	0.5955	0.5924
1:4	0.7940	0.7606
1:5	0.9925	0.9091

fabrication of hand exoskeleton in terms of sterility and cannot be used for all hand sizes. For this reason, the suggested material is silicon rubber which can be washed or sterilized with alcohol. Furthermore, the pulley system needs to be optimized for mechanical durability and less friction.

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