PULLEY-BASED MCKIBBEN ACTUATOR MECHANISM FOR ADJUSTABLE SOFT HAND REHABILITATION SPLINT

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DEDICATION

Dedicated, in thankful appreciation

for support, encouragement, and understanding

to my beloved father, mother, brother, and sister

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ABSTRACT

Hand rehabilitation robots were developed to assist in rehabilitation procedures conducted by rehabilitation professionals. However, current hand rehabilitation robots are mostly made from heavy and rigid structures that caused discomfort and fitting issues to the patients. McKibben actuator is a type of soft actuator that could be used in hand rehabilitation robots for its flexibility and light weight. However, it has a limited contraction ratio for the required range of motion for finger flexion. In this thesis, a pulley mechanism is proposed to improve McKibben actuator's contraction ratio while providing the required contraction force. A double groove pulley made of a hybrid of gear and pulley is proposed to enhance McKibben's actuator contraction ratio. Various pulley ratio was studied to find optimum contraction ratio and its relation to contraction force. A pulley ratio of 1:4 increases the contraction ratio from 19.85 % to 76.67 % but reduces the contraction force from 42.68 N to 9.69 N. Hence, pulley ratio of 1:2 was implemented to the McKibben linear actuator based on its optimized 39.72 % contraction ratio and 20 N contraction force for the soft splint application. Next, an adjustable finger size soft splint with fixed wrist motion was developed. It consists of three parts, namely pulley–based McKibben actuator, wrist component, and McKibben ring actuators. The wrist component was designed with an adjustable strap buckle while the finger insertion part utilized the elasticity of McKibben ring actuator during contraction to fit a wide range of sizes. The size range for wrist and hand circumference is 12 cm – 21.6 cm and 15.8 cm – 22.3 cm respectively, which fit 90 % of Malaysian young adults. The soft splint was tested on two healthy subjects. At 400 kPa supply pressure, the bending angle of the finger joints achieved was [71.8^o, 72.8^o, 18.7^o] for Metacarpophalangeal, Proximal Interphalangeal and Distal Interphalangeal respectively. The range of motion achieved by the soft splint is lower than the functional range of motion, but higher compared to other research works. The subjects were able to grasp and lift objects of different shapes including a box, cylinder, and irregular shape under 250 g while wearing the soft splint. The developed soft splint with adjustable McKibben ring actuators and pulley–based McKibben linear actuator could initiate finger motion and assist object grasping for a possible clinical hand rehabilitation assessment.

ABSTRAK

Robot pemulihan tangan telah direka bentuk untuk membantu dalam pemulihan yang dijalankan oleh pakar pemulihan. Tetapi kebanyakan robot mempunyai bingkai yang berat dan tegar, menambahkan lebih beban dan ketidakselesaan kepada pesakit. Penggerak McKibben adalah sejenis penggerak lembut yang boleh digunakan dalam robot pemulihan tangan kerana ia mempunyai fleksibiliti yang tinggi dan ringan. Tetapi penggerak McKibben mempunyai nisbah penguncupan terhad untuk mencapai sudut sendi jari yang diperlukan dalam kelenturan jari. Dalam tesis ini, mekanisme takal telah dicadangkan untuk meningkatkan nisbah penguncupan sementara menghasilkan daya penguncupan yang diperlukan. Takal alur berganda yang diperbuat daripada hibrid gear dan takal diusulkan untuk meningkatkan nisbah penguncupannya. Beberapa nisbah takal telah dikaji untuk mendapat nisbah penguncupan optimum dan hubungannya dengan daya penguncupan. Dengan menggunakan nisbah takal 1:4, nisbah penguncupan ditingkatkan daripada 19.85% kepada 76.67% tetapi mengurangkan daya penguncupan daripada 42.68 N kepada 9.69 N. Oleh itu, nisbah takal 1:2 telah diterapkan dalam penggerak linear McKibben dengan nisbah penguncupan 39.72 % dan daya penguncupan 20 N yang telah dioptimumkan untuk belat lembut. Selepas itu, belat lembut dengan saiz jari boleh laras dengan penetap pergerakan pergelangan tangan telah direka bentuk. Ia terdiri daripada tiga bahagian, iaitu penggerak McKibben berasaskan takal, komponen pergelangan tangan, dan penggerak cincin McKibben. Komponen pergelangan tangan direka dengan tali boleh laras manakala bahagian penyisipan jari menggunakan keanjalan pengaktif cincin McKibben semasa penguncupan supaya sesuai dengan pelbagai saiz. Julat saiz untuk lilitan pergelangan tangan dan tangan adalah 12 cm – 21.6 cm dan 15.8 cm – 22.3 cm, yang sesuai dengan 90% orang dewasa muda Malaysia. Belat lembut telah dicuba pada dua subjek yang sihat. Pada bekalan tekanan 400 kPa, sudut sendi jari yang dicapai adalah [71.8^o, 72.8^o, 18.7^o] bagi Metacarpophalangeal, Proximal Interphalangeal dan Distal Interphalangeal. Julat gerakan yang dicapai oleh belat lembut adalah lebih rendah daripada julat gerakan berfungsi, tetapi lebih tinggi jika dibandingkan dengan ROM yang dicapai oleh kerja-kerja penyelidikan lain. Subjek dapat mengangkat objek pelbagai bentuk termasuk kotak, silinder, dan bentuk yang tidak teratur di bawah 250 g dengan memakai belat lembut. Belat lembut yang dibangunkan dengan penggerak cincin McKibben boleh laras dan penggerak linear McKibben berasaskan pulley mampu memulakan gerakan jari dan membantu pencengkaman objek untuk penilaian pemulihan tangan klinikal.

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LIST OF ABBREVIATIONS

WSO	-	World Stroke Organization
ADL	-	Activities in Daily Living
NASAM	-	National Stroke Association of Malaysia
CPM	-	Continuous Passive Motion
AAROM	-	Active-Assisted Range Of Motion
HSB	-	Hospital Sungai Buloh
HSA	-	Hospital Sultanah Aminah
ROM	-	Range of Motion
SMA	-	Shape Memory Alloy
OSHA	-	Occupational Safety and Health Administration
CAD	-	Computer-Aided Design
FPL	-	Flexor Pollicis Longus
FDS	-	Flexor Digitorum Superficialis
FDP	-	Flexor Digitorum Profundus
EPB	-	Extensor Pollicis Brevis
EPL	-	Extensor Pollicis Longus
ED	-	Extensor Digitorum
EI	-	Extensor Indicis
EDM	-	Extensor Digiti Minimi
WHO	-	World Health Organization
MCP	-	Metacarpophalangeal
PIP	-	Proximal Interphalangeal
DIP	-	Distal Interphalangeal
PFA	-	Perfluoroalkoxy

LIST OF SYMBOLS

r_p	-	Pulley Groove Ratio
d_L	-	Diameter of Load Groove
d_M	-	Diameter of McKibben Groove
L_L	-	Contraction Length on Load
L_M	-	Contraction Length from McKibben
L	-	McKibben Length
τ_L	-	Torque of the Load Groove
τ_M	-	Torque of the McKibben Groove
F_L	-	Pulling Force from the Load Groove
F_M	-	Pulling Force Applied on McKibben Groove
θ_{MCP}	-	Angle of Metacarpophalangeal Joint
θ_{PIP}	-	Angle of Proximal Interphalangeal Joint
θ_{DIP}	-	Angle of Distal Interphalangeal Joint
σ	-	Standard Deviation
N	-	Number of times experiments conducted
x_i	-	Reading taken at every 50 kPa
μ	-	The average reading at every 50 kPa

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CHAPTER 1

INTRODUCTION

1.1 Problem Background

A stroke happens when there is an interruption in the blood supply to parts of the brain, causing it to be malfunction and become severely damaged. According to World Stroke Organization (WSO), an average of 13.7 million cases of first-time strokes happen all over the world each year [1]. While in Malaysia, there are over 50,000 new cases reported yearly [2], and stroke was listed as one of the top 10 causes of hospitalization [3]. Luckily, advancement in technology and awareness about stroke has increased the survival rate of stroke patients to 90 %. But, up to 70 % of stroke survivors leave the hospital with disabilities [2].

The severity of the disability depends on the affected area of the brain. It varies from a decrease in strength to complete paralysis. The most commonly affected area of the whole body is the arm with almost 3 out of 4 stroke survivors suffer from arm weaknesses [4]. Stroke survivors with arm weaknesses or disabilities will face difficulties in carrying out activities in daily livings (ADL) such as maintaining hygiene and feeding. Some are even unable to return to work. Not only does it affect the stroke survivors but also their family members, especially when they were one of the family breadwinner [5]. About 40 % of the stroke survivors were of working age [6]. Therefore, rehabilitation is important for stroke survivors to sustain their lives.

Rehabilitation is the process of helping the patients to regain the movement of important muscle parts. At Hospital Sultanah Aminah (HSA), hand rehabilitation was conducted using a dynamic splint as shown in Figure 1.1 to hold the wrist of the patients at 15 degrees for effective finger motion. The occupational therapists will then assist them with finger flexion manually. It must be conducted at least half an hour a day for several weeks for effective training, and hence is very labour-intensive.

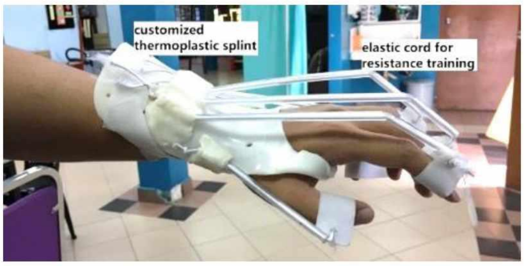

Figure 1.1 Dynamic splint

In some cases, the professionals are unavailable to treat the patient and to guide the rehabilitative session. This means that rehabilitation services cannot be provided to every stroke survivor. During the 1st Malaysia Stroke Conference in 2019, Datuk Dr. Noor Hisham Abdullah, the director-general of Health, mentioned that there were only 107 specialists from all sectors in Malaysia and there was a need for at least another 200 specialists to handle stroke patients [7].

To overcome this shortcoming, rehabilitation robotics has been introduced to assist rehabilitation over the past decades. There were clinically proven results showing that it can help patients with hand mobility impairment to perform repetitive exercises and accelerate the recovery of function and muscle strength of the affected arm [8], [9]. It can also control and reproduce movements precisely [9]. However, due to the heavy and rigid structures, most of the rehabilitation robots can cause patient discomfort. There is also fitting issue to align the center of rotation between robot and human finger joints [10].

Many research groups have shifted their focus towards soft robotics because of its promising potential in future robotic development. Soft robots are robots made of soft materials and therefore possess advantages that are unachievable with rigid robots. They also fit decently onto body parts and reduce abrasion onto humans, which makes them a better choice for prosthetics and wearable technology [11], [12].

Although some studies focused on the development of soft wearable robots for hand rehabilitation, there has been little discussion on their wearability on spastic hands. Most of the patients are unable to straighten their fingers to wear the devices.

In most cases, the rehabilitation devices needed to be shared among patients but most of the devices require customization to each patient.

Soft robots are controlled by using soft actuators, devices that can deform when stimulated to produce mechanical power. The soft actuators are able to move in many ways, including bending, twisting, curling up, stretching, and mimicking muscle movement, which are useful in certain tasks such as grasping [11]. Soft actuators are also simple in structure, lightweight, and adaptive to the environment [13].

One such soft actuator is a McKibben pneumatic actuator. It consists of a rubber inner tube surrounded by a double helix braided sleeve and actuates like biological muscle where the muscle will grow in width and shrink in length. It has a high power-to-weight ratio due to its lightweight design. The elastic inner tube that was stretchable also promoted a safer interaction with humans due to it's compliance and softness. The main restriction of the McKibben actuator is its limited contraction ratio. The thin McKibben actuator (S-muscle SM series [14]) shown in Figure 1.1 can only achieve a contraction ratio of 22 % at 300 kPa [15].

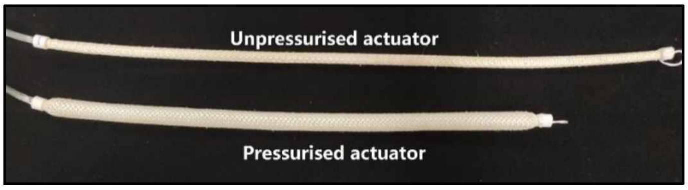

Figure 1.1 Thin McKibben actuator by S-muscle [14]

A number of research groups have proposed several ideas to improve the contraction ability of the McKibben actuator. Prof Koichi Suzumori Research Group altered and changed the fabricated structure of McKibben to increase the detour route and further increase the contraction ratio [16]–[19]. The best contraction ratio that they achieved was 37 % [17]. Other proposed ideas include nested muscle arrangement and internal pulley mechanism. The internal pulley mechanism gives the highest contraction ratio which is 50 % [20]. Although these mechanisms are improving the contraction ability, there is room for further improvements to increase the efficiency of the McKibben actuator.

Therefore, this research proposes a soft splint with adjustable size and improved wearability on spastic hands, controlled by pulley-based thin McKibben actuator with improved contraction ability. It is expected that the research contributes to the development of a user-friendly and comfortable hand rehabilitation device that helps to reduce the workload of occupational therapists in providing rehabilitation services to stroke patients in the near future.

1.2 Problem Statement

Soft actuated hand rehabilitation robot could provide better user experience while being safer and more comfortable from the flexibility and lightweight nature of its actuator material. Two major types of soft actuators were used, which are bending actuator and contracting actuator. The pneumatic bending actuator is capable of initiating finger flexion [21]–[24], but the bending of the actuator is uneven. The highest bending only occurs at a certain part of the actuator[23], [25]. While for contracting actuator, the retraction of shape memory alloy (SMA) that was coiled into spring shape was used to pull the cable to initiate finger motion. However, it has a low efficiency where the strain produced is only 2-5 % [26], [27].

There are some research works that implemented McKibben actuator in hand robots for hand rehabilitation. McKibben actuator is a contracting actuator that was known for its high contraction force and similar characteristics to human muscle. It has a contraction ratio of 22 % when supplied with 300 kPa [15]. However, a pressure of 600 kPa was needed to initiate a half flexion, which already exceeds the pressure limit. For higher displacement, a longer McKibben is required due to its limited contraction ratio [16]–[19]. There were several ideas proposed by other research groups to improve its contraction ability by modifying the fabricated structure of McKibben muscles and could improve the contraction ratio by at most 32.1 %. Another study [20] which uses internal pulley mechanism shows an increase in the contraction ratio to 50 % [20]. But there is still room for further improvement to increase the efficiency of the McKibben actuator by improving the design of the pulley.

Most of the soft rehabilitation robots developed focused on the actuation mechanism but very few focused on wearability and size. Occupational therapists from HSA have mentioned that they tried to use a rehabilitative glove to assist in hand rehabilitation, but they encountered several issues. They are providing therapy to patients with various hand sizes, while the glove could only fit a certain range of sizes. There is also fitting issue to align the center of rotation between robot and human finger joints [10]. Most of the patients suffer from spasticity and it is hard for them to hold their fingers straight for the donning of the full-covered glove and need something can be easily worn.

1.3 Research Objectives

The objectives of the research are:

(a) To design a pulley-based mechanism to improve the contraction ratio and contraction force of McKibben linear actuator.

(b) To develop an adjustable size soft splint that initiates finger flexion using silicone and McKibben ring actuators.

(c) To evaluate the functionality of the soft splint for its range of motion and object grasping function.

1.4 Research Scope

The scope of the research includes the fabrication of a pulley-based McKibben linear actuator to improve its contraction ratio based on the pulley design.

The soft splint was designed to initiate the flexion of only four fingers, which includes the index finger, middle finger, ring finger, and little finger with the usage of on/off control system. The thumb which has more degrees of freedom in motion was excluded because its structure is different from the other fingers, and it contributes the least to the grip strength. On/off control was used because of the non-linearity of the McKibben actuator.

The soft splint is designed by referring to the available hand anthropometric data of Malaysian young adults [28], [29]. Most of the stroke patients are senior citizens but there is insufficient hand anthropometric data on senior citizens. There are many challenges in collecting a new set of anthropometry data including cost, time, and variety of ethnicity. Therefore, the soft splint was designed based on the available data of Malaysian young adults.

Several parameters can be used to evaluate the functionality of the soft splint. In this research, the soft splint will only be evaluated for the range of motion (ROM) that each finger could achieve and compare with functional ROM. Also, the evaluation will be conducted on object grasping performance with three objects of different shapes, which are box, cylinder and irregular shapes.

Finally, the soft splint was tested on two healthy subjects, including one male and one female Malaysian young adult. Clinical trial on actual stroke patients was not conducted because ethical approval procedures and involvement of professionals were needed for clinical trial but will be considered in the future work.

1.5 Organization of Thesis

This thesis was organized into five chapters. In Chapter 1, the background of the study and problems that need to be solved were introduced. Solutions proposed were also included, along with the scope of the study.

In the next chapter, stroke and human hand were studied. The background of stroke rehabilitation was also presented. Literature review on hand rehabilitation robots that were available in the market or under development were also presented and summarized for comparison. A few types of soft actuators that were applied in hand rehabilitation devices were studied. McKibben actuator was studied in detail with the review of ideas proposed to improve its contracting ability. Lastly, the concept of pulley was studied.

The development of the proposed soft splint was described in Chapter 3, which started with preliminary testing to obtain information that was essential for the mentioned design. The process of design, fabrication, and improvement of the design was also discussed in this chapter.

Chapter 4 presents the setup and results of the experimental testing of the proposed double groove pulley and soft splint. The analysis of the data collected from the experiments and comparison with the reference data were also presented.

Finally, Chapter 5 presents the summary of this research. Future works were also suggested for further improvement of the soft hand splint.

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LIST OF PUBLICATIONS

A.1 Indexed Journals

1. **S. Z. Ying**, A. A. M. Faudzi, N. K. Al-Shammari, and Y. Sabzemeidani, "Continuous Progressive Actuator Robot for Hand Rehabilitation," *Eng, Tech. & App. Scie. Res.*, vol. 10, no. 1, pp. 5276-5280. 2020.

A.2 Conferences / Proceeding Papers

1. A. A. M. Faudzi, **Z. Y. Sii**, and M. Sayahkarajy, "Space Optimization Technique for McKibben Soft Actuator using Pulley System," in *International Graduate Conference on Engineering Science and Humanities (IGCESH 2018)*, 2018, pp. 1-3.
2. **Z. Y. Sii** and A. A. Faudzi, "Space Optimization for McKibben Muscles Using Double Groove Pulley", in *International Conference of Universal Wellbeing 2019 (ICUW 2019)*, 2019.
3. **Z. Y. Sii** and A. A. M. Faudzi, "Retractable Double Groove Pulley for Optimization of the Contracting Ability of McKibben Actuator", in *Regional Conference in Civil Engineering and Sustainable Development Goals in Higher Education Institutions 2020 (RCCE n SDGs 2020)*, 2021.