A NEW FIBER BRAIDED SOFT BENDING ACTUATOR FOR FINGER EXOSKELETON

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Dedicated, in thankful appreciation
for support, encouragement and understanding
to my beloved mother, father, brothers and sisters

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ABSTRACT

This thesis presents a design, development and analysis of a novel bending-type pneumatic soft actuator as a drive source for a finger exoskeleton. Soft actuators are gaining momentum in robotic applications due to their simple structure, high compliance, high power-to-weight ratio and low production cost. Smaller and lighter soft actuator that can provide higher power transmission at lower operating air pressure will benefit finger actuation mechanism compared to motorized cable and pulley-driven finger rehabilitation devices. In this study, a soft actuator with new bending method is proposed. It is based on fibre reinforcement of two fibre braided angles of contraction and extension characteristics combined in a single-chamber cylindrical actuator. Another four design parameters identified that affect the bending motion and the actuating force were the air chamber diameter, position of fibre layer reinforcement, fibre reinforcement coverage angle, and silicone rubber materials. Geometrical and material parameters were varied in Finite Element Method (FEM) simulation for design optimization and some parameters were tested experimentally to validate the FEM models. The effects of fibre angles (contraction and extension) on the bending motion and force were analyzed. The optimized actuator can generate bending motion up to 131° bending angle and the end tip of the actuator can make contact with the other base tip at only 240 kPa given input pressure. Both displacement simulation and experimental testing results matched closely. Maximum bending force of 5.42 N was generated at 350 kPa. A wearable finger soft exoskeleton prototype with five optimized bending actuators was tested to drive finger flexion motion of eight healthy subjects with simulated paralysis conditions. The finger soft exoskeleton demonstrated the ability to provide gripping force of 3.61 ± 0.22 N, gained at 200 kPa given air pressure. The device can successfully provide assistance to weak fingers in gripping at least 240 g object. It shows potential in helping people with weakened finger muscle to be more independent in their finger rehabilitation exercise.

ABSTRAK

Tesis ini membentangkan pembangunan penggerak lenturan lembut jenis pneumatik terbaru sebagai sumber pemacu dalam menggerakkan jari. Penggerak lembut mendapat momentum dalam aplikasi robotik kerana strukturnya yang mudah, sifat pematuhan yang tinggi, nisbah kuasa kepada berat yang tinggi dan memerlukan kos produksi yang rendah. Penggerak lembut yang lebih kecil, ringan dan dapat menjana kuasa penghantaran yang tinggi pada pengendalian tekanan udara yang lebih rendah dapat memanfaatkan mekanisme penggerak jari jika dibandingkan dengan penggerak jari menggunakan motor dan takal. Dalam kajian ini, kaedah lenturan baru untuk penggerak lembut diusulkan. Ia adalah berdasarkan kepada dua sudut corak gentian yang mempunyai sifat penguncupan dan pemanjangan digabungkan dalam penggerak silinder tunggal. Empat lagi parameter reka bentuk telah dikenal pasti dapat memberi kesan terhadap gerakan lentur dan daya penggeraknya, iaitu isipadu ruang udara, kedudukan lapisan gentian, liputan sudut gentian dan bahan getah silikon. Parameter geometri dan bahan telah diubah dalam simulasi Kaedah Unsur Terhingga (FEM) dalam pengoptimuman reka bentuk dan ada di antaranya yang diuji secara eksperimen untuk mengesahkan model FEM yang direka. Kesan daripada sudut gentian penguncupan dan pemanjangan terhadap gerakan lentur dan daya lenturan telah dianalisa. Penggerak yang telah dioptimumkan boleh menjana 131° sudut lenturan dan hujung akhir penggerak dapat menyentuh hujung yang lainnya hanya pada 240 kPa tekanan udara. Kedua-dua keputusan anjakan daripada analisis simulasi dan eksperimen hampir berpadanan. Daya lenturan sebanyak 5.42 N dapat dijana pada 350 kPa. Penggerak lembut yang telah dioptimumkan menunjukkan keupayaan cengkaman kuasa sebanyak 3.61 ± 0.22 N pada 200 kPa tekanan udara. Sarung tangan kerangka luar menggunakan lima penggerak lenturan yang optimum telah diuji untuk membengkokkan jari lapan orang yang sihat yang dilemahkan. Berdasarkan ujian daya cengkaman yang dilakukan, sarung tangan kerangka luar ini dapat membantu menggerakkan jari yang lemah sekurang-kurangnya dalam menggenggam objek seberat 240 g. Ia menunjukkan potensi dalam membantu orang yang lemah otot jarinya untuk lebih berdikari dalam melakukan rehabilitasi senaman jari.

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LIST OF ABBREVIATIONS

FBBA	-	Fiber Braided Bending Actuator
SOFT-EXOS	-	Wearable Finger Soft Exoskeleton
FEA	-	Finite Element Analysis
FEM	-	Finite Element Method
3-D	-	Three-Dimensional
ADL	-	Activities in Daily Living
MCP	-	Metacarpal-Phalangeal
PIP	-	Proximal Interphalangeal
DIP	-	Distal Interphalangeal
DOF	-	Degree-of-freedom
OSHA	-	Occupational Safety and Health Administration
PAM	-	Pneumatic Artificial Muscle
FMA	-	Flexible Microactuator
CS	-	Case Study
SIM	-	Simulation
EXP	-	Experiment
YM	-	Young’s Modulus
PR	-	Poisson’s Ratio
CAD	-	Computer-Aided Design
CNC	-	Computer Numerical Control
MS	-	Microsoft
RTV	-	Room Temperature Vulcanizing
SD	-	Standard Deviation
ABS	-	Acrylonitrile-Butadiene-Styrene

LIST OF SYMBOLS

F - contraction force

D_o - actual diameter of the fiber layer at initial state

P - applied input pressure

θ_o - fiber braid angle before pressurization

ε - contraction ratio

θ_C - extension fiber angle

θ_E - contraction fiber angle

d_{cham} - air chamber diameter

r_{fiber} - fiber layer radius

t_i - inner rubber layer thickness

t_o - outer rubber layer thickness

Z - fiber spacing between two consecutive fiber

α_C - contraction fiber coverage angle

α_E - extension fiber coverage angle

M_{in} - inner layer rubber material

M_{out} - outer layer rubber material

d_{total} - actuator total diameter

L_{total} - actuator total length

L_{cap} - end cap fittings length

L_f - length of actuator body with fiber reinforcement

α_{braid} - coverage angle of fully crossed interlaced fiber braid

C_{180} - circumference length of 81^{o} fiber braid structure

C_{90} - circumference length of 72^{o} fiber braid structure

C_{30} - circumference length of 46^{o} fiber braid structure

C_{20} - circumference length of 35^{o} fiber braid structure

Z_{small} - fiber spacing between two consecutive smallest element

C - circumference length of full circle

P - pitch

R - revolution

Z_{new} - displacement of the tip at Z direction from the centre end point of actuator’s proximal end

Φ_{B} - bending angle

$\# SIM$ - bending angle from simulation data

$\# EXP$ - bending angle from experiment data

$\overline{\mathrm{X}}_{TF}$ - mean of the generated tip force from 3 experiment trials

s_{TF} - standard deviation of the generated tip force from 3 experiment trials

X_{i} - generated tip force value of each trial

N - total number of trials

$\overline{\mathrm{X}}_{G}$ - mean of the generated grip force from 3 experiment trials

s_{G} - standard deviation of the generated grip force from 3 experiment trials

X_{G} - generated grip force value of each trial

μ_{G} - mean of the generated grip force representing total of 8 subjects

SD_{G} - standard deviation of the generated grip force representing total of 8 subjects

N_{P} - total number of subjects participated in the testing

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CHAPTER 1

INTRODUCTION

1.1 Background

It was reported that 49% of older people that face difficulties in performing physical tasks were caused by musculoskeletal diseases such as Arthritis, 13.7% by heart disease, 12% by injury, 11.7% by old age, 6% by lung disease, and remaining 2.9% were caused by stroke [1]. Among those contributing factors, people with stroke was reported to be facing difficulties in using upper extremities and performing basic activities of daily living [1].

Worldwide, stroke is the second commonest cause of death and a leading cause of adult disability [2]. According to statistics announced by National Stroke Association of Malaysia (NASAM), stroke is the third highest cause of death in Malaysia [3]. Nearly 40,000 people in Malaysia suffer from stroke every year, affecting adults more than children. Some studies shows that majority of stroke cases occurred due to cerebral infarction (50% - 87%), followed by cerebral hemorrhage (20% - 30%) [4]–[7]. Other most frequent risk factors include hypertension, diabetes mellitus and previous stroke [5], [8]–[13].

Paralysis, a common disability resulting from stroke, may range from complete inability to move to less than total strength, thus affecting the stroke survivors in their daily activities, such as causing difficulty in walking and grasping objects. Depending on the severity of neurological deficits, 19% of stroke survivors were very severely disabled, 4% of them severely disabled, 26% moderately disabled, 41% minor disabled and no disability shown for the remaining 10% [14].

After completing stroke rehabilitation, a study shows 11% of the stroke survivors still very severely and severely disabled, 11% moderately disabled and another 78% shows minimum or no disability [14]. Other study in Singapore shows 91.9% of the stroke survivors can independently conduct self-care activities after completed rehabilitation [13]. Other than stroke survivors, elderly and patients with prolonged intensive care (ICU) stay [15] can also exhibit general weakness and problems in coordinating that need physical rehabilitation.

Early stage, repetitive and continuous rehabilitation can help the brain relearns lost skills much faster and with more significant results. The assistance of robotic devices, might also promote a cost-effective therapy for stroke survivors to maintain their ability to move after receiving standard in-hospital rehabilitation [16]–[18]. Rehabilitation devices specifically designed for restoring hand function, usually known as finger exoskeleton must be able to at least assist flexion motion of fingers. Rondi Blackburn, a medical professional developed a theory that repeated exercises of the affected hand and fingers will open up new pathways of communication between the brain and the stroke-affected area (American Heart Association). Strength, mobility and precision exercises are types of exercises usually being performed to stroke survivor rehabilitation.

With the advancements in robotics and mechatronics research in the last decade, rehabilitation robotics has become an active research area. Rehabilitation Robotics is the application of robotic technology to the rehabilitative needs of people with disabilities as well as the growing elderly population [19]. The main restriction in the current finger rehabilitation robot system is the complexity in its structure which requires metallic or plastic alignment in every finger joint in the finger actuation system [20]–[27]. Heavy unit from plastic and metal load can contribute to wearer discomfort.

To counter these problems, Soft Actuator, also known as Rubber Actuator, is a pneumatic driven actuator which can offer simpler structure, high power-to-weight ratio, lightweight, comparative low cost, and easy maintenance [28]–[31], suitable to be utilized in finger exoskeleton. It converts energy from compressed air into various motions depending on its design. In comparison to hydraulic actuator, pneumatic actuator is relatively small in size, requires smaller tank for air storage and is lightweight. It is also easy to control with only simple on-off type control. It does not produce heat except for friction, thus the risk of accidental fire is low. This can promote safer interaction with human.

Soft actuation by using Soft Actuator is still a young approach in robotics engineering and currently developing. There a few research groups around the world that implement soft actuator in robotics application. To name a few, there was Prof. Koichi Suzumori Research Group established at Okayama University in the early 2000s. The group focuses on developing soft actuators mechanism in various field [28]–[50], especially in object manipulation and medical assistance. In the same university, there was also Prof. Toshiro Noritsugu Research Group that implement soft actuation in rehabilitation assistance [51]–[54]. Other groups that are currently actively involved in soft actuation research are the Whitesides and Conor J Walsh Research Group from Harvard University. Since 2011, they have been rapidly developing soft actuator technology especially in the field of biomimetic and assistive wearable rehabilitation [55]–[63].

Although some studies in the recent years have focused on applying soft actuator in finger exoskeleton for object grasping manipulation [51]–[54], [64], there has been very little discussion on the gripping force assistance and these studies have been limited to the generated actuator force, not gripping force from the soft exoskeleton unit.

This research proposed a novel soft exoskeleton to assist fingers weak in finger flexion motion by utilizing a new bending-type soft actuator. The research is expected to contribute highly to the development of a user-friendly, comfortable, safer and more powerful finger exoskeleton prototype, where it can help in reducing therapists’ workloads in performing therapy tasks to stroke survivors in the future.

1.2 Problem Statements

Wearable devices designed to suit many parts of body such as shoulder, elbow and finger assist system are gaining popularity at present due to their portability and can support movement in weak muscles especially in stroke survivors. Robots or devices that are comfortable to wear and easy to be used will increase user motivation in performing the exercises, thus hastening recovery. Simple mechanical design with high flexibility and proper softness in motion and touch is required in order to provide efficient therapy [58], [63], [65].

Although some finger exoskeletons show promising results in providing grasping motion [51], [53], [54], [61] the size and force performance of bending-type actuator utilized in the actuation system can still be improved. In addition, little data of the assisted grasping force has been found [51], [53], [54], [61]. Smaller size bending-type soft actuator with increased power transmission at lower operated air pressure is required.

A new soft actuator design suitable for power soft actuation is proposed based on fiber braided reinforcement in McKibben actuator. McKibben pneumatic artificial muscle (PAM) is known to be high achieving contraction force actuator due to fiber braided layer structure incorporated at the outer layer of its cylindrical body structure [66]. The fiber layer restrains radial contraction while promoting contraction forces. Due to its high force capability driven by the fiber braided reinforcement, two different fiber braided angles in a single chamber were proposed to obtain desired bending motion and force for finger flexion actuation. Currently, bending soft actuator prototype shown from literature that uses fiber braided contraction and extension fiber angles reinforcement are not mechanically interlocked and bulky [38].

1.3 Objectives

The followings are the objectives of the research:

1. To simulate, fabricate and optimize the proposed bending soft actuator using two fiber braided angles (contraction and extension) in one chamber.
2. To validate the 3-D FEM models of the proposed bending soft actuator with the fabricated actuator models.
3. To implement finger soft exoskeleton that utilized the optimized bending soft actuator in finger flexion.

The main objective of this research is to develop a new single chamber fiber braided bending-type actuator (FBBA) using combined contraction and extension-type fiber reinforcement. The new bending mechanism of soft actuator developed in this research is utilized in finger soft exoskeleton and is expected to be able to provide grasping assistance in weak fingers at least in holding light objects.

1.4 Scope

The followings are the scope of the research:

1. FBBA design development using technical mathematical drawings of combined contraction and extension fiber angles reinforcement in one chamber.
2. Proof of FBBA bending concept in FEM simulation analysis using MARC$^®$ Mentat software.
3. FBBA 3-D FEM optimization and analysis based on several design parameters (air chamber diameter, position of fiber reinforcement, rubber materials, fiber reinforcement coverage angle) performed with FEM software, MARC$^®$.
4. Fabrications of the proposed FBBA using molding, rubber bonding and fiber knitting techniques.
5. Evaluation of the FBBA based on tip trajectory plot, bending angle and generated tip force performance.

6. Implementation of the optimized FBBAs onto the glove (SOFT-EXOS) utilizing rubber band and elastic textile attachment.
7. Evaluation of FBBA in SOFT-EXOS implementation based on the measured mean value of the assisted grip force in 8 healthy subjects.

1.5 Contributions

The main research contributions of the research are as follows:

1. A new actuator bending actuator concept using two fiber braided angles (contraction and extension) in one chamber that can produce bending motion is introduced.
2. A new 3-D FEM model designed with combined fiber pattern reinforcement is developed and validated by experimental testing of the fabricated actuator model.
3. A new prototype of finger exoskeleton utilizing the novel bending actuator and flexible glove attachment is developed.

1.6 Organization of the Thesis

The thesis is organized in five chapters. Background of the research field, introduction to the recognized problems that need to be solved, the proposed solutions to the research problems, the scopes of the study, and some recognized contributions of the research are introduced in Chapter 1.

In Chapter 2, the literature review on finger flexion methods in finger exoskeleton are presented in several actuating mechanisms, for example pulley system-operated, motor-operated, and pneumatic-operated. Soft actuation mechanisms showing different resulting motions, particularly in pneumatic and hydraulic operated system applied in diverse applications are also presented. Various bending concepts proposed from different groups of researcher studied in flexible and high force applications are also studied.

The research flow and methodology used in the development of the proposed actuator design and the implementation of the actuator design in simulation, experimental testing and application- based study are shown in Chapter 3.

Chapter 4 mainly presents the results of FEM simulations and experimental testing of the proposed actuators that were evaluated by displacement and force performance. FEM model validation and optimization results in several geometrical parameter changes are also presented. In addition, the feasibility study conducted on healthy subjects in order to evaluate the performance of the proposed actuator design implemented in the finger soft exoskeleton system is presented.

Finally, the summary of research contributions and future solutions gained from the study are covered in Chapter 5.

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