



DEPARTMENT OF MECHANICAL ENGINEERING

MECHATRONICS

UNDERGRADUATE RESEARCH JOURNAL

Volume 8 – December 2015



THE UNIVERSITY OF
AUCKLAND
Te Whare Wānanga o Tamaki Makaurau
NEW ZEALAND

ENGINEERING

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The *University of Auckland Undergraduate Mechatronics Research Journal* is published annually by the Mechatronics Engineering Group of the Department of Mechanical Engineering, located within:

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Preface

Mechatronics research is basically the integration of mechanical, computer, and electrical engineering in order to design innovative smart devices, machines, systems, and production processes. At the University of Auckland, we focus on systems design and integration using mechanisms, sensors, actuators, controls, computers, and real-time software, with primary applications into healthcare, medicine, sports, manufacturing, and agriculture.

The Bachelor of Engineering (Honours) degree in Mechatronics Engineering was launched in 2002. In addition, we also offer ME and PhD degree programmes in the Mechatronics Engineering specialisation.

As part of the BE degree, fourth year students (working in pairs) are required to complete a research project, or Final Year Research Project (FYRP). These projects also represent the range of our academic staff members' research interests and activities. This journal, for students and by students, is a collection of a few outstanding samples of FYRPs completed each year. Since contributions to this journal are voluntary, it provides only a small glimpse into the diverse student research activities in the field of Mechatronics at The University of Auckland.

This 2015 issue is a special edition featuring Biomechatronics projects. It consists of seven papers written by students who took our newly introduced elective course "MECHENG 736 Biomechatronic Systems". The research project is part of course assessment and can be carried by a group of four undergraduates or a single postgraduate. This year the students were given two research topics to choose from, which were "Design and Applications of a Robotic Exoskeleton for Rehabilitation of Temporomandibular Disorder" and "Biomimetic Mechatronic Design and Applications of a Robotic Esophageal Simulator".

Wish all of you enjoy reading this issue.



Peter Xu
Professor & Chair in Mechatronics Engineering

December 2015

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Design of a Robotic Exoskeleton for Rehabilitation of Temporomandibular Disorder

Rubio, Mary Jocelyn and Shardlow, Timothy and Zander, Marius

Abstract— This report outlines the work done on the redesign of a robotic exoskeleton used for rehabilitation of temporomandibular disorders. An existing exoskeleton, which uses a helmet fitted onto a patient's head, as well as a four-bar-linkage which emulates jaw motion during chewing, is used to aid in mouth opening and closing training for a patient with TMD. This device is the basis of the new design, where improvements on features such as general aesthetics, patient comfortability, as well as safety, have been considered and applied. In addition to this, the actuation design as well as the motion control of the device has also been considered and is discussed in detail in the report.

I. INTRODUCTION

The masticatory system consists of the teeth, jaw bones and muscles, and the temporomandibular joint or TMJ, and it is responsible for a person's ability to move their jaw for tasks such as chewing. Problems in the TMJ or masticatory muscles may result in temporomandibular disorders or TMD, where a patient may experience pain or be unable to open their mouth successfully. Such disorders would require physical as well as neurorehabilitation in order to aid in the patient's recovery.

A current exoskeleton design has been developed as a means for rehabilitating patients with TMD. This exoskeleton exercises the patient's joint and muscles by aiding in mouth opening and closing. The overall aim is therefore to redesign and improve on this existing exoskeleton. Doing so would involve modifying the current design to improve its current features and functionality. It would also involve designing the actuator and the motion control of the exoskeleton.

II. RELATED WORK

A. Biological system

The Temporomandibular joint is one part of the masticatory system. To get an understanding of the biological system, which we are focusing on, an introduction of the masticatory system is given.

The masticatory apparatus consists of an upper and lower jaw. The upper jaw, called maxilla, is attached to other bones that make up the skull. The lower jaw, called mandible, is connected to the skull by muscles, therefore, it can move. The two joints on each side of the jaw between skull and mandible are called temporomandibular joint or TMJ. An articular disc which is soft tissue, separates the condyle and the temporal bone at the skull and enables the jaw to move along the bone. This joint is special in comparison to other joints of the human body, because instead of following a

specific trajectory the TMJ movement occurs in an envelope of motion in three-dimensional space. The maximum range of this movement is described by Posselt's Envelope.

B. Temporomandibular Disorder and Rehabilitation

Problems in the TMJ or the masticatory muscles may result in a patient having reduced ability when it comes to moving their jaw or opening their mouth. Temporomandibular disorders or TMD encompass these problems, but each individual case would come with its own factors and symptoms.

A 2007 published paper in the Journal of Dentistry [1] describes these factors and symptoms in TMD. The key symptoms in TMD were described to be pain in the TMJ or in the masticatory muscles, noise during jaw motion, and restricted mobility of the mandible. This paper mainly looks at the prevalence of these key symptoms in patients who have shortened dental arches, and a 9 year follow-up study was conducted in order to determine the correlation of shortened dental arches and TMD.

On the other hand, another paper in the 2004 Journal of Oral Rehabilitation [2] deals with the psychological factors such as stress, anxiety, and depression in patients with TMD. This paper discusses how different subgroups in TMD experience varying psychological effects, but the overall study does indicate that patients with TMD experience an increase in stress, anxiety, depression as well as somatization, where the patient undergoes psychological distress as a result of the physical disorder.

C. Use of Robotics in TMD Rehabilitation

More and more robotic devices can be found in medical applications. The advantages for the use of robots for rehabilitation purposes are a motivating effect, accuracy, objective behavior and adaptability.

The 2010 paper by Diegel, Potgeiter, Etzel, Xu and Wang [3], describes the design of a wearable device specifically for the use of rehabilitation of TMD. In this device, the 3D movement of the jaw is simplified to a 2D trajectory in the sagittal plane. This motion is executed through the use of the four-bar linkage, and it was derived from analyzing the chewing motion undergone by the jaw. The overall design of this device consists of a helmet, the actuator, the linkage mechanism, and the chin support.

In addition to this exoskeleton design, other robots have been developed which have 6 degrees-of-freedom and are also used for movement training for the patient. A 2003 paper in the IEEE International Conference in Robotics and Automation [4] describes a robot used for jaw opening and

closing, as well as lateral movement training. This robot has 6 degrees-of-freedom, with a 3 degree-of-freedom manipulator used for a doctor to send commands to the main device. This 3-DOF manipulator would then be able to set parameters, such as the jaw open angle, and this allows for custom modifications of the robot which can be made unique for each patient. The design of this robot also takes into account patient comfortability, in that the patient would not see the mechanism while they are using it. This would therefore reduce psychological overbearing and stress on the patient.

A similar device with 6-DOF and used for mouth opening and closing is also detailed in the 2000 paper also for the IEEE Conference on Robotics and Automation [5]. The robot described also has a load cell and a strain gauge to measure the bite force from the patient on the X, Y and Z axes. It also includes various safety measures, such as an emergency stop switch, a software limit, and mechanical and electrical stoppers.

D. Sensors and Actuators

Background knowledge of various sensors and actuators was required prior to designing the mechatronic system of the wearable device.

A 2014 paper in the Sensors Journal [6] details the use of wireless surface electromyography sensor (SEMG). The paper addressed the issues that SEMG have, namely that it does not provide real time monitoring, has a long processing time, and is not effective for wireless healthcare systems. The paper addresses these issues by proposing to transmit compressed data at intervals wirelessly opposed to continuous raw data.

Another technical paper in the 2010 Microsystem Technologies journal [7] presents a method of producing a water tight packaging of MEMS actuators. This packaging is done by surrounding the MEMS actuator with a wall that has an opening for the actuator to extend out. Then a lid is flipped onto the constructed base making the clearance hydrophobic. MEMS actuators will not be suitable for the type of TMJ device that is being proposed, although this type of water sealing technique could potentially be used on a MEMS sensor that could be utilized in the TMJ rehabilitation device.

Lastly, a paper in the 2012 Journal of Physical Therapy Science [8] discusses how placement of EMG sensors affect the data collected. This was achieved by placing the EMG sensors on different locations on an adolescent male subject and recording the data. A similar procedure could be done to find the optimal sensor position of EMG sensors if they are to be used in the TMJ rehabilitation device.

III. CONCEPTUALIZATION AND SPECIFICATION

An overall design was developed which stemmed from analyzing the quantitative and qualitative specifications that the robotic exoskeleton needed to be met. These requirements included safety, as well as comfortability and ease of use for

the patient using the device. In addition to this, the design was also made as an improvement on an existing wearable device design, as described in the next section.

A. Redesign of a Pre-Existing Device

The design of the TMJ rehabilitation device was based on the device presented in paper by X.Y. Wang, W.L. Xu, Senior Member IEEE, K. Etzel, J. Potgieter and O. Diegel [3]. This device was analysed to identify its strengths, weaknesses and areas to improve upon. Figure 1 shows a diagram of this design, as well as the parts it consists of.

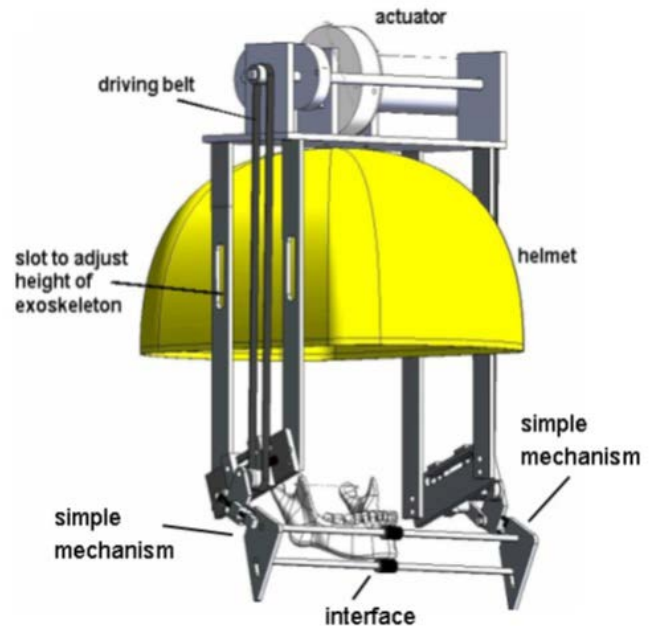


Figure 1: Previous Design of the Wearable Device [3]

The device's main disadvantages were that it was not adjustable to fit a range of head sizes through the use of a helmet as its means of attaching the device to the head of the user; the actuator drive belt of the device was poorly positioned such that it was running parallel to the side of the user's head without any guard; also as the device was purely a mechanical device there was no feedback or control; and lastly, the device had no safety features which would be critical in a real world application. The current device also had its advantages, such as the simple two degree-of-freedom mechanism which did well to simplify the complex movement of the jaw, and the cross bars used which were adjustable to fit a range of jaws.

From the analysis of the previous device, key aspects were identified that needed to be improved for implementation in the new rehabilitation device. These aspects included how the device will attach to the user, the actuation, the safety features, and data acquisition.

B. Overall Design

The final design is a head mounted exoskeleton that attaches to the user's head via a harness and chin pad. The actuation method for the device would be a pair of linear actuators that are coupled to perform a 2 DOF motion, and this is shown in Figure 2.



Figure 2: Actuator Positioning

The device has software based limiters and physical limit switches integrated into the actuators to control the range of motion of the device, while also having integrated force sensors to measure force on the patient. The device will be connect to a PC with an interface for the clinic to use, with data recording to monitor patient rehabilitation. Additional features could be introduced as supplementary add-ons, such as a mobile application and an interactive game to help stimulate patient interaction and assist with rehabilitation. Figure 3 below shows the overall design of the wearable device, and Appendix A also shows this device in different planes of view.

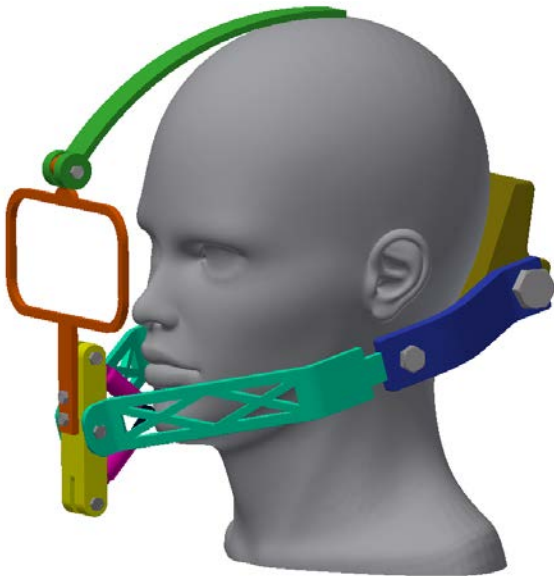


Figure 3: New Design for the Wearable Device

B. Actuators

The simple 2 DOF mechanism in the current device is one of its key features, but the actuation and actuator positioning has room for improvement. With the aim of replicating the 2 DOF motion of the current device, other actuation methods were investigated. The key considerations when deciding the actuation for the new device were the strength, size, positioning on the device, reliability, and the response time.

A hydraulic system was investigated, which would ensure strength but would also require a pump system and this may be unsuitable for clinical use. DC motors were also investigated, since these could produce the required strength, be of a reasonable size, and be reliable. However, it would suffer from the same problem as the current device [3], as their position would require a gear or belt drive system, which could interfere with the user.

MEMS actuators were also investigated, and these had the advantage of being biomedically compatible. Due to their size, however, they lacked the strength needed for the proposed design. Lastly, linear actuators were investigated which would be able to replicate the 2 DOF motion of the current device by coupling two of them together. However, this would require them to be positioned in line with the face, below the mouth. Despite this, linear actuators could also produce enough strength to achieve the task.

C. Head Attachment

How the device was to be attached to the user was broken down into two areas, how it would attach to the user and how the device would attach to the patient's jaw. The key considerations for this would be secure fit, adjustability and comfortability.

Another helmet design was investigated but its lack of adjustability made it undesirable, even though it would give a solid base to mount the mechanisms of the device. Neck and shoulder braces were also investigated since this would hold the device well and help distribute the weight over the neck and shoulder. These were ruled out because they would also be difficult to adjust for a range of body and neck sizes, and because the brace would limit the patient's movement and may force them into an uncomfortable and stiff position for the length of the treatment. Lastly a head harness was investigated, this would be easily adjustable, would be secure enough for this application, and would not restrict movement or position of the patient. Of the three investigated methods, having the device attach to the user's head via a harness was determined the best option. This harness would be lightweight and would be fastened to the patient in such a way that it will not obstruct their view.

The second consideration was how the device would attach to the user's jaw. This would have to be strong, comfortable and able to be adjusted for a range of jaw sizes. An in-mouth attachment was investigated, like a sports mouth guard. The mouth guard would give an optimal force on the jaw for the downward motion, but would require another platform under the jaw for the upward motion of the rehabilitation. A mouth guard could be adjustable by having the clinic have a range of cheap and disposable blank mouth guard molds that could be individually fitted for each patient. This option would also make the device more hygienic as there it would mitigate the chances of any cross contamination between patients.

Lastly, a chin pad was also investigated, and this would be molded such that it would connect to the ridge on the jaw just under the mouth and it would also connect to the underside of the chin. This would allow for support for both the upward and downward strokes of the rehabilitation and

having this produced to be cheap and disposable will help reduce hygiene concerns in a clinic situation.

D. Safety Features

The current device has little to none safety features, and this would be a key area of development for the new device. The safety features main goal would be to set limits for the actuators so the system does not cause pain or discomfort to the user.

Software based safety features were investigated, and these could be easily varied via software to adapt to the different requirements of the patients, although their effectiveness would be limited to the response time of the system and would require some type of interface for adjusting the limits. Traditional limit switches could also be used to set the upper and lower limits of the device's motion, and these would have to be mounted on a rail to ensure they could be adjusted to fit different users, or they could be integrated into the actuators to give a system upper and lower limit.

Another safety concern for the device is how much force is being applied to the user. This needs to be monitored to ensure no damage is done to the user and does not experience any pain or discomfort. The force sensor could be placed in the mouth between the user's upper and lower jaw or at the end of the actuators. By having the sensor in the user's mouth this would give an actual value of the force being experienced by the user, as opposed to a force sensor on the actuators which would give a calculated force, even though having the sensor in a mouthpiece would cause problems regarding how it would be adjusted for multiple users as well as hygienic concerns.

E. Data Acquisition and Control

The current device was purely mechanical, and to improve rehabilitation and add a monitoring functionality, data should be collected during the treatment to allow for medical analysis of the patient. Also, by integrating electronic and control systems into the device, this will allow for greater control of the device and thus making targeted rehabilitation more effective. This could be achieved by having the device tethered to a PC, which would give the system a lot of processing power and would allow for expansion or additional sensors, such as EMG. A PC would also allow for an interface to be built so the device would be easy to use by clinic personnel who may have no knowledge of programming and controllers.

In addition, a PC link would allow power to be supplied along the same bundle of cables. A microcontroller could also be used. This would have the convenience of the device being self-contained and not require additional equipment to run. With the use of a battery pack, the device could also be untethered so the user can have the freedom to use the device anywhere. However this would come at the cost of a user interface and would require a basic understanding of control and programming to retrieve the data, or set software restrictions.

IV. MECHATRONIC DESIGN AND DEVELOPMENT

The robotic exoskeleton, to be designed in this research project, is a mechatronic device and therefore needs to be designed and specified in respect to actuators, sensors, and control. Due to the fact that this project is not a design-and-built project we only focus on two categories which are actuators and control.

A. Actuation Development

One of the biggest changes regarding the former device is the actuation system. In the former device the actuators were placed on the top of the helmet, which results in the need for cables and linkages to transfer the torque of the motor to the end-effector which is the attachment at the chin. This arrangement causes uncertainties due to complexities that cannot be modeled. Furthermore, for a safe and accurate motion control we need sensors which measure the force at the chin. Using the former actuator arrangement and integrated sensors would result in non-collocated control. Non-collocation is a term used if actuators and sensors are not placed at the same position and can cause insufficient control and instability of the controlled system [9]. Another disadvantage that was mentioned in the paper of the former device was a "not optimal" force distribution within the device mainly caused by the long thin bars which are attached to the chin. To overcome these problems, the fundamental idea is to place actuators directly in front of the chin so that the force applied by the actuators is directly applied to the end-effector. Therefore, no linkage can be used to implement the desired jaw movements, which automatically demands the need of a software-based motion control and actuators which can perform an arbitrary movement in two dimensions (see chapter III).

To keep the movement simple and clear only linear actuators are in line for this purpose. There are many different types of actuators available. One way to divide the different types into two main categories is to describe them as compliant or non-compliant. On the one hand, there are a lot of advantages to use compliant actuators in biomechatronic system. On the other hand, we try to observe and control the end-effector position as accurate as possible which excludes most of the compliant actuators. For example, it is not possible to control pneumatic actuators precisely except at full stops. There are approaches to get an accurate position control but the infrastructure would be too complex for our device [10].

One often used linear actuator is called traveling-nut actuator, i.e. a nut attached to the moving cylinder of the actuator moves along a rotating screw. The transfer of rotational motion into linear motion is often realized by a ball-screw mechanism which decreases the amount of friction compared to a rigid coupling without balls. The actuator is normally driven by a DC-motor, which has a linear and simple characteristic; therefore, it can be controlled excellently.

In respect to our device there is one big drawback for the use of a traveling nut actuator. On the one hand, we want a non-compliant actuator; on the other hand, we want to guarantee that large forces between the human and the device can be compensated in order to prevent the patient from

injuries. The fact that the coupling of the traveling-nut actuator has a large gear ratio results in self-locking effect in case force is applied at the end-effector. Therefore, the aim is to include an overload protection into the actuator which can decouple the nut and the screw at high forces. Such a mechanism is often used as an overload protection at the coupling between two rotating arbors of a gear. Those overload protections are often realized by balls which are clamped between disc springs. Due to the usage of balls as a coupling between the screw and the nut in our device the overload protection can easily added to the actuator as displayed in Figure 4. The red blocks symbolize an elastic material whose purpose is to couple the nut and the screw up to a specific force limit.

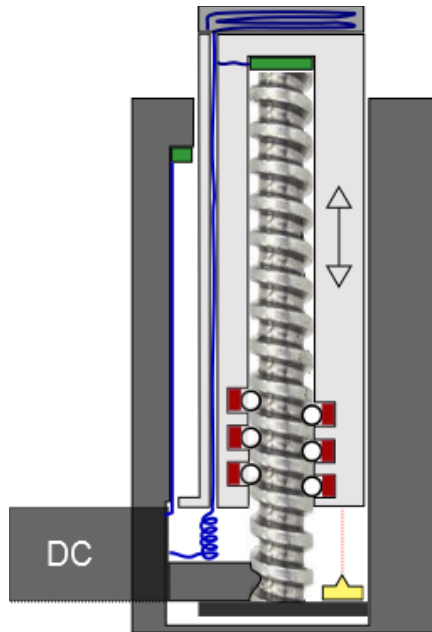


Figure 4: Schematic design of the proposed actuators

Unfortunately, the decoupling of the overload protection cannot be detected by a position sensor at the DC motor. Often a revolution count is integrated in the DC motor so that the position of the actuator can be detected by considering the gear ratio. To solve this problem an additional sensor has to be added that can directly measure the displacement of the moving nut, or the moving cylinder respectively. One possibility would be the usage of a laser-displacement-sensor. Such a sensor is indicated in yellow in Figure 1.

Another sensor is added at the top of the actuator to implement the collocated control as mentioned at the beginning of this chapter. A detailed specification of the sensors is not given in this paper.

B. Motion Control

The design of our device requires a sophisticated control system which ensures an accurate motion and a safe use.

The overall control concept consists of a motion control, a safety system and the adjustment to individual patients. The motion control also includes the translation of the motion into actuator positions. This concept is shown in Figure 5.

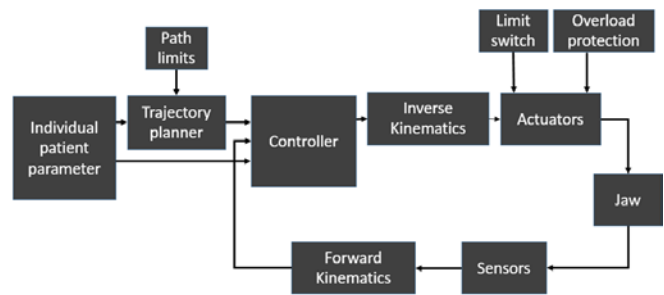


Figure 5: Control overview

The mechanical device provides many adjustments so that the actuators can be set at a fixed reference point relative to the mandible. However, the motion still needs to be adjusted in the software. For this purpose the jaw size of the patient has to be integrated into the control loop. This is done in the block “Individual patient parameter”. Furthermore, this point is used as an interface between doctor and device, and therefore, sensitivity and ability of the patient can be set to vary the intensity of the controller interaction.

The choice of a rehabilitation method is set in the block “Trajectory planner”. Different disorders need a slightly different treatment, so that different motion patterns can be selected. For example, the neuro-rehabilitation of TMDs after stroke is based on motor learning which results in neuro plasticity and is most effective if the desired motion is repeated many times [11]. To achieve this, a repetitive motion pattern should be implemented in this part of the control system. As an additional safety feature a path limit restricts the freedom of motion. This path limit is basically Posselt’s envelope and describes the area of maximum movement of the mandible during mouth opening and closing.

The main part of the control system is of course the controller. Our device based on the theory that a movement is relearned by assisting the patient by physically guiding a movement. This so called active assist exercise is mentioned as suboptimal in some research papers which is termed “guidance hypothesis”. It states that physically assisting a movement changes the dynamics of the task so that the task learned is not the target task [12]. Because providing too much assistance may have negative consequences in learning, a strategy called “assist-as-needed” was developed. This means the patient is assisted just as much as needed to accomplish the task. The implementation of such a controller is to create a deadband or tunnel around the trajectory of the movement in which no assistance is provided. Outside of this tunnel a restoring force pushes the patient in the direction of the desired trajectory. The size of the area can be adjusted with progress of the patient.

In addition, an EMG signal can be used to control the amount of force that is applied when assistance is needed. In this approach the patient decide the movement to be performed, while the controller compensates for weakness so that the force is proportional to the EMG signal which is needed to perform the movement [13].

For the patient’s learning progress, it can be helpful to get a visual feedback of the performed tasks. According to the

theory of motor learning, the patient has to observe the error between the desired and actual movement [14]. The error, the desired trajectory, the actual position and the assistance are can be displayed on a screen to realize this visual feedback.

Another part of the control concept is the interface between the software (controller) and the hardware (actuators and sensors). The whole previously mentioned control strategies are described in one two dimensional coordinate system. However, the actual movement is generated by two one dimensional actuators. Therefore, the control system is supplemented by two blocks which cover the kinematics of the system.

The transformation of signal from the initial coordinate system into input signals of the actuators is called inverse kinematics. This term is used in robotic devices to describe the position of linkages (in this case the actuators) in respect to a given end-effector position.

The displacement of the two actuators is described by the equations

$$A_1 = |\overrightarrow{POS} - \overrightarrow{A_{1ini}}| \quad (1)$$

$$A_2 = |\overrightarrow{POS} - \overrightarrow{A_{2ini}}| \quad (2)$$

\overrightarrow{POS} is the vector of the desired position in the initial coordinate system and A_{ini} as the initial position of the actuators at their fixed reference points.

The more complex part is the transformation of the collected sensor signals into the force distribution in the initial coordinate system. This transformation is termed forward kinematics. To derive the transformation, the actuator geometry is shown in Figure 6.

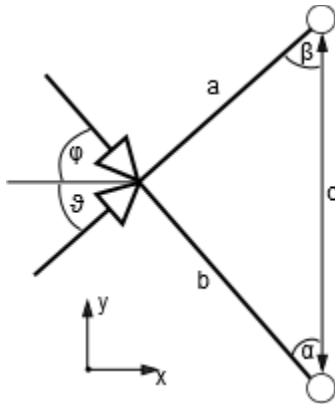


Figure 6: Actuator geometry

The distance between the joint of the actuators is indicated by the lower letter c, and the displacements of the two actuator is indicated by a, and b respectively. The aim is to derive the force distribution in the initial coordinate system with the data given by the two force sensors at the tip of the actuators. This is done by geometric calculation as follows:

$$\alpha = \cos^{-1} \left(\frac{a^2 - c^2 - b^2}{2bc} \right) \quad (3)$$

$$\beta = \cos^{-1} \left(\frac{b^2 - a^2 - b^2}{2ac} \right) \quad (4)$$

$$\varphi = 90^\circ - \alpha, \vartheta = 90^\circ - \beta \quad (5)$$

$$F_x = F_2 * \sin(\varphi) + F_1 * \sin(\vartheta) \quad (6)$$

$$F_y = F_2 * \cos(\varphi) + F_1 * \cos(\vartheta) \quad (7)$$

After adding the equations of the kinematics to the control system a closed loop system can be established. Both, force and position are fed back to the controller to realize the assist-as- needed control.

V. CONCLUSION

This report shows the progress done in the re-design and modification of a pre-existing exoskeleton device used for rehabilitation of temporomandibular disorders. Literature reviews were done in order gain an understanding of the masticatory system; the disorders associated with the system, as well as rehabilitation techniques which aid in patient recovery from such disorders.

The design presented in this report eliminates the need for a helmet, and instead uses a lightweight harness to fasten it onto the patient. The four-bar linkage has also been discarded, with two actuators used instead, as a means to mimic the jaw movement. Overall, the safety, aesthetics and the functionality of the exoskeleton has been taken into account in order to produce the final design. The actuator design and motion control of the exoskeleton was also considered and discussed in detail in the report.

APPENDIX A – OVERALL DESIGN

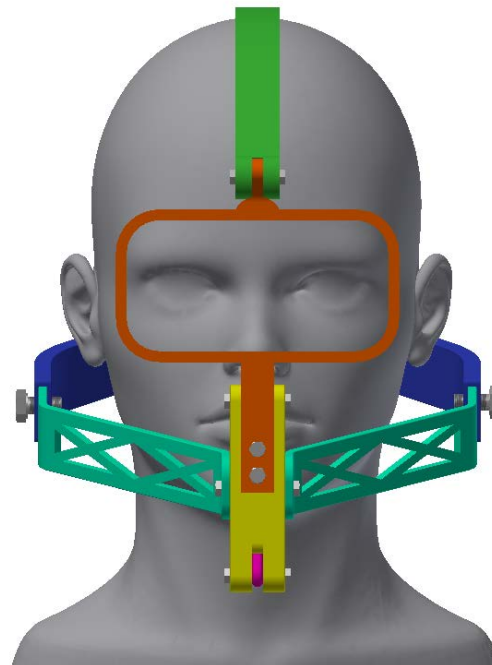


Figure 7: Front view of the design

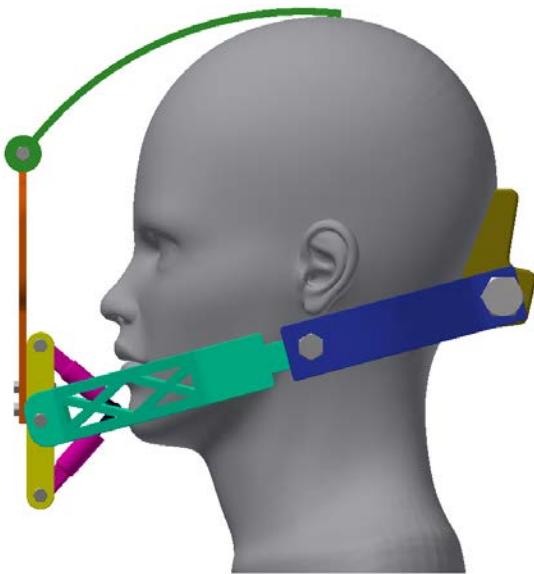


Figure 8: Side view of the design

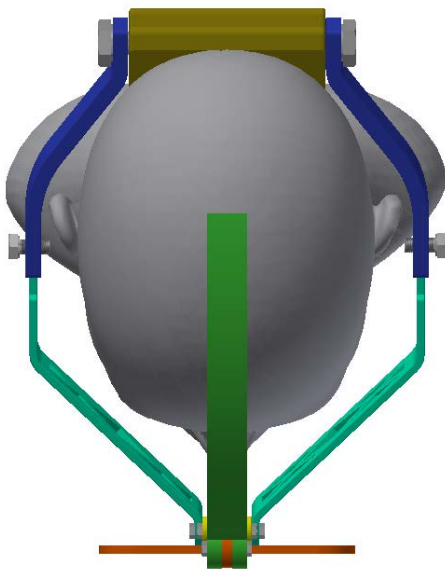


Figure 9: Top view of the design

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Biomimetic Mechatronics Design Of A Robotic Esophageal Simulator

James Greenfield; Haram Hwang; Ash Moorhead; Alec Wang

Abstract— This paper outlines a proposed design for a new bio-robotic esophageal simulator which uses a novel pneumatic cylinder compression system to produce a physiologically similar peristaltic wave. Extensive research has been conducted regarding the physiology of the human esophagus as well as into previous esophageal bio-robot studies to produce a novel design that offers advantages for potential future research. Various aspects of the design have been considered with solutions proposed for the actuation, control and sensing mechanisms of the esophageal simulator. The pneumatic piston cylinder actuation system allows generation of multiple peristaltic waves throughout the modelled esophagus through the use of an electro-pneumatic interface. The sensor system allows local measurements of the external and internal pressure, bolus viscosity and bolus velocity to aid in research and analysis of the esophagus movement. Whilst it is purely a conceptual design, it is believed that the design has several key advantages over existing robotic esophageal simulator systems.

I. INTRODUCTION

Globally the population is becoming increasingly older, with the median age rising in societies around the world, and therefore the health and welfare of elderly people is becoming more of a concern. Dysphagia (difficulty in swallowing) is a medical condition which is more likely to affect the elderly due to age related changes in the swallowing physiology. It is estimated that as many as 600,000 people are affected by dysphagia every year in the U.S. [1]. While dysphagia is quite often a symptom of an underlying disease, it can also be a life threatening condition by itself. Diseases such as aspiration pneumonia (where an infection occurs in the lungs due to the accidental inhalation of food or saliva) are often a result of the dysfunction of the swallowing reflex [2]. Consequently, the biological mechanism of swallowing is currently the subject of a lot of academic research.

The prediction and modelling of bolus transport through the esophagus is of particular interest to food scientists who develop texture modified foods (TMF) for the management of dysphagia. The majority of current research utilizes mathematical models or in-vivo medical investigations in an attempt to predict the bolus transport behavior of TMF. However, these techniques are more reflective rather than predictive and rely on qualitative outcome measures which are inherently hard to scientifically compare and assess [3]. Furthermore, a lot of ethical issues are prevalent when dealing with in-vivo investigations. In order to develop effective TMF, food scientists need quantitative data of the bolus transportation process. Hence, in more recent investigations a shift has been made towards the robotic simulation of the human esophageal system.

Robotic modelling investigations possess the potential to provide quantitative rheological and tribological data with greater repeatability than current investigation methods. It also does not require the participation of subjects, enabling researchers to perform more invasive swallowing experiments with no risk to the health and safety of subjects. The main objective of this research project was to develop a novel bio-robotic esophageal simulator which would provide researchers with biologically faithful data for the human esophageal system.

II. RELATED WORK

A. The Biological Esophagus System

The esophagus is a muscular tube that begins at the inferior end of the laryngopharynx, runs through the inferior aspect of the neck and esophageal hiatus in the diaphragm, before ending in the superior portion of the stomach [2]. Its primary function is the transportation of food, which has been formed into a cohesive bolus during the oral phase of digestion, into the stomach [2, 3, 4, 5, 6]. In adults, the esophagus is normally between 200 and 260 mm long and is composed of three layers; an internal mucosal layer which is encompassed by a circular muscle layer and an outer longitudinal muscle layer as depicted in Figure 1 [6]. The circular and longitudinal muscle layers are responsible for peristalsis, the mechanism of bolus transport down the esophagus. As the bolus passes down the esophagus, these muscles contract and relax to generate peristaltic waves which propel the bolus into the stomach.

B. Existing Bio-robotic Esophageal Simulators

The esophagus is a complex system to robotically emulate. This complexity has resulted in a plethora of different esophageal simulator design approaches and strategies. Chen et al. and Dirven et al. developed one particularly successful design [3, 7, 8, 9, 10]. This design is comprised of 12 segments which each have four pneumatically pressurized air chambers that are sequentially inflated to compress the inner conduit. This design is very faithful to the true biological esophageal system as it is inherently compliant and mimics

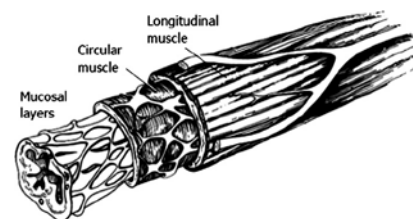


Figure 1. Physiology of esophagus

peristaltic movement. However, there are also a series of

limitations surround its ability to model the tail of the peristaltic wave [3, 7, 10].

Several other methods of robotic actuation have also been investigated. Watabe et al. developed a system that utilized shape memory alloys (SMA) which are heated in a pre-defined order to cause contractions and thus creating a peristaltic wave [11]. Mikanohara et al. investigated the use of a pH sensitive gel with an acid-autocatalytic reaction in order to simulate the contraction waves of the human esophagus [12]. Carpi et al. implemented electroactive polymer (EAP) that transduces an electric signal into mechanical actuation. The esophagus was modelled by a segmented EAP tube where a voltage was applied to cause radial expansion and sequentially removed across segments to cause contraction, effectively mimicking the peristaltic movement of the esophagus [4].

Expanding on the utilization of a bio-robotic esophagus as a simulator, one study investigated the implantation of an artificial esophagus in-vivo [13]. Miki et al utilized a heat activated SMA integrated with a Gore-Tex vascular tube as an esophageal replacement. This fairly successfully mimicked the true peristaltic movement of an actual esophageal system, but actuation of the system caused damage to the surrounding living tissue. There was also a degree of uncertainty over the limitations of the device with the authors noting that the forces generated by the system may not be great enough to transport all food types.

C. Other Bio-inspired Peristaltic Robots

Several studies involved the development of bio-inspired robots that simulate peristalsis for other purposes. Whilst these systems are not designed specifically for simulation of the human esophageal system, aspects of each design have the potential to be incorporated into a robotic esophageal simulator. Nugoho et al. developed a spiral coil robot that utilizes peristalsis to inspect pipe networks [14]. Inspired by the movement of an earthworm, this robot is broken into several segments that can move independently with spiral elements that can expand and compress radially. Forward propagation is produced by increasing the spiral length while the increase in diameter generates friction between the body of the robot and the inner pipe wall. Alternatively, Bon et al developed a peristaltic pump using straight-fiber-type artificial muscles driven by pneumatic pressure [5]. Like the robot developed by Nugoho et al. this system was also inspired by the movement of the earthworm. The flexibility of this system allows it to be very adaptable and as it is pneumatically actuated it is also naturally compliant. The peristaltic movement generated by this system transports fluids forward whilst sealing the pipe behind it. This mechanism of actuation could potentially be altered for use in an esophageal simulator.

D. Sensing and Measurement of Esophageal Systems

One of most crucial elements of bio-robotic esophageal simulators is the implementation of sensors to measure rheological and tribological data. This data is the most important output of the system, but currently it is very difficult

to accurately acquire [7]. Many methods exist to sense and measure the tribology and rheology of the esophageal system including manometry, videofluorography, functional magnetic resonance imaging (MRI) and endoscopy [8]. Sudip et al. performed a study where the esophageal peristalsis of 75 subjects was quantified using high resolution manometry [15]. It was found that the assessment of what constitutes as clinically relevant abnormality is a difficult task due to the lack of standardization of manometry apparatus and clinical testing protocols. However, as this was an in-vivo study, there were limitations to the sensor hardware which had to be safe for implementation into the subjects. Bio-robotic simulators remove the human safety aspect in the measurement methodology and so it is possible to utilize a wider range of sensor systems, allowing the obtaining of important data for research purposes.

E. Summary of Related Work

While several different bio-robotic esophageal simulators have already been developed for research purposes, all of them have several limitations. Current technologies do not mimic the completely smooth, compliant and continuous peristaltic motion of the biological esophageal system to a high degree of precision. This mainly due to an over simplification of actuation technologies and a lack of sensory information [7]. As such, robotic modelling is yet to have a noticeable impact on the design of TMF. Therefore, there is a need to develop a novel bio-robotic esophageal simulator that has a more biologically faithful actuation system and an improved sensory system.

III. DESIGN CONCEPTUALIZATION AND SPECIFICATION

Through assessing the biological esophageal system and existing bio-robotic esophageal simulators, a biologically inspired design specification was devised. These were the core design requirements upon which conceptualization focused on. The quantitative design specifications are summarized in Table 1. This ensured that the final proposed design would best model the human esophagus in a physical sense.

Table 1. Design specifications

Esophageal Length	200-260 mm
Esophageal Diameter	20 mm
Wavefront Length	30-60 mm
Wave Velocity	2-4 cm/s
Wave Shape	Single inflection, polynomial or sinusoidal

In addition to this it was also important that the following qualitative features were met within the design:

- Compliance
- Continuous actuation
- Peristaltic transport
- Sequentially actuated architecture

The qualitative features ensure that the designed

bio-robotic esophagus would best represent the movements and actions of the biological esophagus. These were derived from understanding the physiological nature of the esophagus but also from the previous bio-robotic work done by other researchers.

It is also crucial that the materials chosen to model the inner conduit of the esophagus are faithful to the properties of the biological system; and hence various elastomer materials were explored for the best possible material to model the biological esophagus.

IV. PROPOSED DESIGN

A. Design Development

The design detailed below in Figure 2 is inspired by the work of Dirven et al. and was considered an iteration on their design as increased control precision is achieved through the use of rigid pneumatic piston actuators [10].

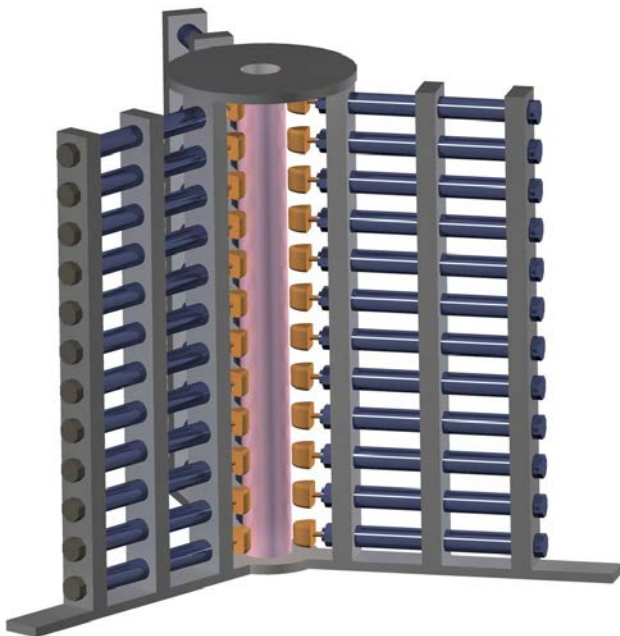


Figure 2. Proposed design

The compliant nature of the soft actuator helped in modelling the elastic nature of the biological esophagus. However, some difficulties were encountered by Dirven et al. when determining the velocity and deformation of the soft actuator, which also acted as the esophageal wall [9]. Consequently the control of this system is difficult and the kinematics and dynamics were found experimentally.

The conduit of the proposed robot will be made from vulcanized silicone rubber. This material has a low Young's modulus and as a result is readily deformed with low force. Possible materials were identified to be Smooth-sil 940 or Eco-flex. The conduit deformation resulting from the rigid piston actuation is easier to predict than deformation of an inflatable chamber because of the well characterised piston and conduit materials. The capability of accurately modelling the deformation induced upon actuation will remove the

necessity of an additional sensor. The deformation can be used in the active compliance controller as position control in conjunction with the velocity. Emulation of the soft contraction properties of the human esophagus is lost through the use of rigid pneumatic pistons, however, this can be easily modelled using active compliance.

The overall base and holder of the design will be 3D printed or laser cut. These methods of manufacture have been chosen based on their relative ease in manufacture and assembly. Furthermore, as both are relatively cost-effective and fast processes, it means that changes can be readily applied as modifications can be made on the CAD model quite easily. Both manufacturing processes offer a robust system that will be strong enough to hold the silicone conduit as well as the pneumatic cylinders.

In order to produce a propagating peristaltic wave, pneumatically actuated pistons are used to occlude the lumen of the esophagus. These actuators are positioned at 12 levels along the length of the conduit and three are evenly spaced at each level. This provides a more consistent radial compression resembling the smooth muscle contraction of the in-vivo esophagus. The pistons have modified cams which are 60° wedges allowing complete occlusion of the conduit as the three cams meet at the centre point of the conduit, as shown in Figure 3a. These cams would be added onto the existing piston rods of the sourced pneumatic cylinders and be made of plastic or lightweight metals such as aluminium. These are essential in performing the complete occlusion of the conduit to push the bolus through to mimic the peristaltic wave behaviour seen with the smooth muscles of the esophagus as seen in Figure 3b [3].

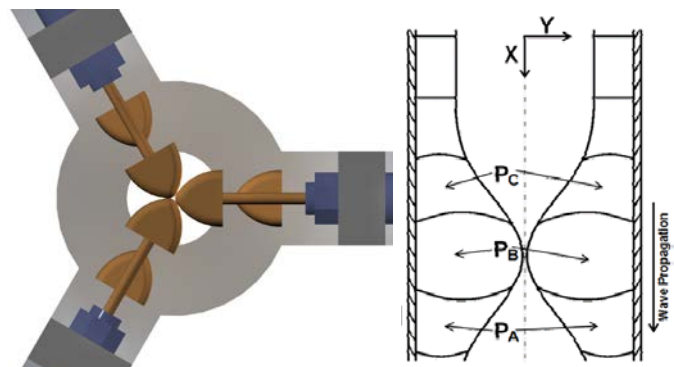


Figure 3. a(left): Occlusion of conduit with 60° wedges; b(right): Mimicking the occlusion of esophagus smooth muscles

An overlapping sinusoidal wave is generated using continuous actuation of multiple pistons as the bolus moves toward the stomach. The wavelength was chosen to be 40 mm and the actuators are required to produce a peak esophageal pressure of 15 kPa [7, 10]. The overlapping wave is shown in Figure 4 demonstrated by the piston positions.

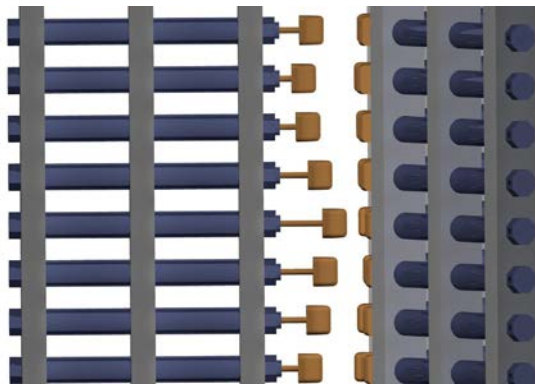


Figure 4. Overlapping wave demonstrated by piston positions

There are potential limitations to this proposed design which have been identified below:

- Not an anatomically similar material used and so the interaction between the conduit and bolus is not necessarily representative of the in vivo response.
- Discrete contractile points, produce a discontinuous peristaltic wave which is not representative of the in vivo contractile wave.

B. Actuation Development

The main form of actuation in this proposed design is pneumatic piston cylinders. These cylinders provide the force in the occlusion of the conduit. The use of rigid pneumatic cylinders offers more control in their movement compared to previous designs such as the expansion of air chambers used by Dirven et al. [10]. With a more rigid control, a more consistent radial compression can be achieved at each level of the esophagus. This also allows the opportunity to model the system more accurately, without the need to derive kinematic and dynamic parameters experimentally as done in previous studies.

A simple pneumatic drive system has been designed as seen below in Figure 5. It comprises of four major components: 1. Air source, 2. Air regulator, 3. Proportional valve, and 4. Pneumatic actuators. The air regulator ensures a constant pressure supply from the source to the actuator whereas the proportional valve controls the airflow and speed delivered to the actuators. This pneumatic drive system would control one level of the 12 proposed in the final design, which corresponds to three pneumatic piston cylinders. Therefore, 12 of the sub-systems seen in Figure 5 will be required for the overall design.

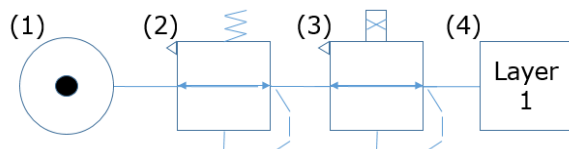


Figure 5. Pneumatic drive sub-system

The 12 sub-system formation is chosen as it allows more actuation control in being able to generate multiple waves through the esophagus, closely mimicking the human body as human swallows multiple bolus in sequence. Furthermore, this also means that there is no need for extra directional valves as part of the pneumatic drive circuit as was seen by

previous designs by Dirven et al. An electro-pneumatic interface can be used in implementing this 12 sub-system control.

An advantage of the proposed design is the vast availability of the components of the system. Due to the size of the esophagus, not much stroke length is required from the cylinders (max 10 mm) and also the pressure required is also quite low (15 kPa for three cylinders). This means that the specifications for the pneumatic cylinders is not very limited, allowing the components to be easily sourced. Most pneumatic cylinders out in the market can provide the actuation pressure required for conduit occlusion and so only size constraints are present. The rigid pneumatic cylinders should have a bore of about 7-10 mm, stroke of >10 mm and length of around 100 mm to ensure it meets the performance requirements but can also aid in keeping the overall system compact.

Spring loaded pneumatic cylinders have been chosen to be the most suitable for optimal performance of the design and an example CAD model of this can be seen below in Figure 6. The spring will aid the pistons to return to the starting position without the need for air pressure. The cylinders are therefore not dependent on the conduit elasticity (which might not be enough) to push the pistons back to the starting positions after occlusion. Furthermore, this also reduces the need for another air inlet for each pneumatic cylinder, decreasing the number of air tubes required and hence the overall physical complexity. As previously mentioned in section 4.1, additional modified cams have been developed for the piston rods to allow for complete conduit occlusion and this can be seen in on the left of Figure 6 below.

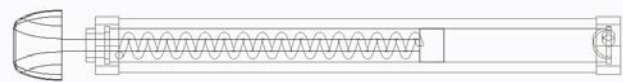


Figure 6. CAD model of spring loaded pneumatic actuator

As aforementioned, an electro-pneumatic interface will be capable of implementing the control of the pneumatic cylinders. This will ensure a sequential activation of the 12 layers of pneumatic cylinders to create the actuation movement of the bolus. This sequential activation is crucial in mimicking the smooth muscle's peristaltic wave formation in the esophagus. An example of this sequential activation can be seen in Figure 4 as the pistons are all at different stroke lengths to accommodate for the bolus movement in the esophagus.

C. Sensor Development

The required sensors are intimately linked to the control of the peristaltic wave created by the contracting pneumatic rings.

In order to control the contraction of these rings a reading of the air pressure within the pneumatic actuator is necessary. This will ensure the expected pressure is the same as the actual pressure exerted on the ring. The intrabolus pressure is

widely considered a measure of the efficacy of the swallowing motion [6], and hence this will be a useful parameter. Additionally, the velocity of the peristaltic wave in the human esophagus is controlled by the CNS and is dependent on the viscosity of the transported bolus. A swallowing robot capable of mimicking this effect would be an advancement of current technology.

In summary, four local measurements are required:

- Air pressure of artificial muscle rings
- Intrabolus pressure
- Bolus viscosity
- Bolus velocity

Intrabolus Pressure Measurement

A manometry catheter will be implemented, by embedding microelectromechanical systems (MEMS) pressure sensors into the flexible inner wall, allowing measurements of the direct pressure applied to the bolus. These sensors would be mounted as twenty-four sets of four circumferential sensors, evenly spaced along the distal axis. This allows for sampling of pressures at two different distal points per actuator unit. The catheter measurement techniques can affect the efficacy of bolus transit through the pharynx [6]. Hence, care must be taken to minimize the vertical profile of the sensors. These sensors will need to have a range of at least 0-15 kPa, with an expected average of 7-9 kPa to provide sufficient range for real esophageal pressures [9]. The air pressure in the pneumatic actuators will be measured automatically by embedded sensors in the actuator valves.

Bolus Viscosity

Bolus viscosity is a more complicated factor to measure, however studies have shown that it determines the amplitude and velocity of the peristaltic waves in a real esophagus [16]. It is also expected that the food bolus will behave as a non-Newtonian fluid. This factor can perhaps be best measured before the bolus is placed inside of the robot, and then assumed to be reasonably constant as it travels down the

esophagus. This assumption should be fine for relatively slow shear rates, which are expected for these operations. A viscometer would be placed at the entrance to the robot and would measure the bolus viscosity by applying a controlled shear rate before allowing the bolus to enter the esophageal simulator. It is expected that the sensor will need a measurement range of 1 mPa.s to approximately 10 kPa.s, which is relatively high, but covers a good spectrum of potential food viscosities [17].

Bolus Velocity

Bolus velocity is another complex quantity to measure in real time. It is likely best measured using an external camera system which tracks a fluorescent labelled material that can be mixed into the food bolus through the use of videofluoroscopy. Cameras sensitive to the wavelength of light that is emitted can then be used as a means of identifying the velocity of the bolus. Due to the low expected velocity, between 10 mm/s and 30 mm/s, a relatively low speed camera will have a sufficient frame rate to produce accurate measurements of velocity given sufficient field of view. An efficient algorithm must be devised that can then calculate the velocity through image recognition in real time.

D. Motion Control

The control system, seen in Figure 7, is based on a controller which is a combination of a microcontroller and a proportional valve. The proportional valve is used to control the pressure which is used to drive the spring-loaded pneumatic actuators. This valve is proportionally controlled by the pressure feedback from the sensors within the pneumatic actuator.

Active compliance will be achieved by the microcontroller adjusting this applied pressure and thus the force on the conduit. The model used is a spring and dashpot, seen in Figure 8, and the equation is $T = k \cdot \theta + b \cdot \dot{\theta}$. This control element takes velocity and position (from modelling of the deformation) as inputs, and adjusts the force into the controller.

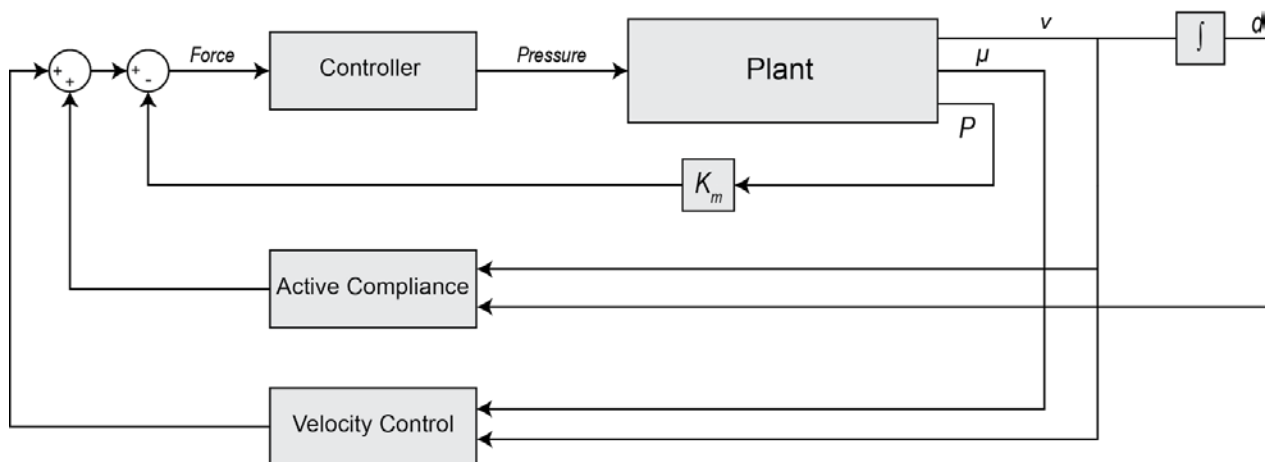


Figure 7. Proposed control system

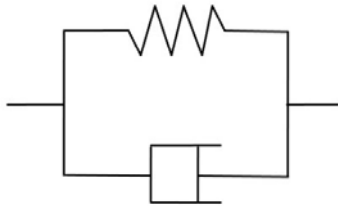


Figure 8. Spring and dashpot model

There is also a control element which controls the speed of the peristaltic wave, this has been found to be related to the viscosity of the food bolus. The viscosity will be measured as the bolus enters the esophagus and the speed of the wave will then be set. This will be a parameter set in the control loop, the microcontroller will then ensure this speed is maintained using velocity feedback from videofluoroscopy imaging of the bolus.

V. CONCLUSION

The proposed esophageal simulator offers superior controllability compared to previous efforts, allowing a system that better mimics the human swallowing motion. The use of rigid actuators reduces the degree of uncertainty in control compared to compliant actuators, while active compliance control allows the device to better mimic a real esophagus. In the proposed design, spring loaded pneumatic piston cylinders allow a complete occlusion conduit, to closely mimic the actions of the smooth muscle of the esophagus in producing the peristaltic wave. The use of 12 different layers in sequential actuation offers a system by which a continuous wave can be achieved and the individual layer control means that the proposed design can generate multiple waves through the esophagus, a major advantage of this design. Furthermore, the sensor mechanisms allow the detection of the external air pressure of the artificial muscle rings, the intrabolus pressure and the bolus viscosity and velocity. Therefore, the design allows capturing a variety of essential information that can be utilized in furthering the research into dysphagia and other esophageal related topics.

VI. FUTURE WORK AND LIMITATIONS

Further work must be done to fully develop the control algorithm that will convert sensor measurements and the user's desired responses into actual movement. The feedback loops, controller gains and the exact microcontrollers will need to be determined. Additionally, the properties of the actuators must be fully characterized to assist in control development and to dimension the rest of the robot. Finally, work must be done to identify which fluorescent markers are most well suited for use in the velocity tracking system. This must cause the least disruption to the bolus rheology possible, such that the experimental results are not confounded.

The proposed design does have some limitations. First, actuation is achieved using 12 discrete layers of pneumatic actuators. This means that the resulting peristaltic waveform will not be perfectly continuous, whereas the contraction in a

real esophagus would be. This places a limit on the accuracy of the simulator, however with sufficiently robust controls the approximation should be more than sufficiently close to not matter. Additionally, the mechanical properties of vulcanized silicone rubber may not match a real esophageal wall well. This means that the properties of the resultant peristaltic wave may not reproduce a biologically accurate motion. With careful control of the actuators, including adjustment of pressures and velocities, it should be possible to minimize the discrepancy however.

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Conceptual Design of an Portable Esophageal Robot Inspired by Vortexes

Jiawen Liang

Abstract— Dysphagia can have negative impacts on cancer patients and shorten their survival time. However, the relationship between food formulation and transport behavior has hardly been discovered. Several attempts have been made to build esophageal robots for simulation purpose and they all have their own advantages and disadvantages. In this research, the conceptual design of a vortex inspired portable esophageal robot will be revealed. It sources power from a 12V battery pack and is expected to deliver smoother flow of fluid or liquid-solid mixture in a confined space.

I. INTRODUCTION

Swallowing is a peristaltic activity to transport parcels (boluses) of solid or liquid foods starting from the oral cavity through esophagus to the stomach. Although peristalsis process is common in the biological organisms, knowledge about the complicated relationship between bolus formulation and transport behavior in human has barely been developed [1]. Dysphagia is a swallowing disturbance that results from various neuromuscular conditions and consequence of systemic weakness[2]. Although palliative care for dysphagia can be offered to maintain pulmonary health and support healthy nutrition[3], uncontrolled dysphagia can aggregate cancer and patients with dysphagia usually have a shorter survival time[4]. As a result, there is a need in developing a robotic device for transporting liquids and semi-solid materials through esophagus so that more information can be collected for clinical diagnosis.

In general the peristaltic wave consists of two components: the circumferential closure of the conduit, and the propagation of contraction along the conduit [5]. The aim of this study is to develop a novel concept for designing a biorobotic device to simulate the mechanical functionalities of human esophageal tract in a biomimetic manner. Ideally such device should be low cost and portable which can significantly extend the range of applications.

The contents of the paper are structured as follows. Section II describes some of the previous research works that are closely related to the esophageal robotic researches. A brief summary of the biological system is provided to each of the researches. Section III gives an overview for the vortex inspiration and the overall design diagram. The mechanism of the vortex esophageal robot is also explained in this chapter. Section IV presents the actuators design, as well as possible applications in the clinical and industrial area. Finally, the conclusions and proposed future works are detailed in Section VI.

II. RELATED WORK

A. Soft Body Actuator

A soft body peristaltic actuator was proposed in 2014 to mimic human swallowing actions. A series of discrete segments were arranged along the food passage to generate a travelling wave [6]. The conceptual design is illustrated in Figure 1. The body of actuator (inflatable chamber in Figure 1) was made of silicone rubber which contained multiple layers of chambers that could expand and contract subject to pneumatic control. Each layer had four chambers with each of them sitting 90 degrees away from the next adjacent chamber. When power was applied all four chambers in the same layer were inflated at the same time to simulate the contraction of human esophagus. Layer activation was a sequential event, starting from the top layer and gradually descended to the bottom layer.

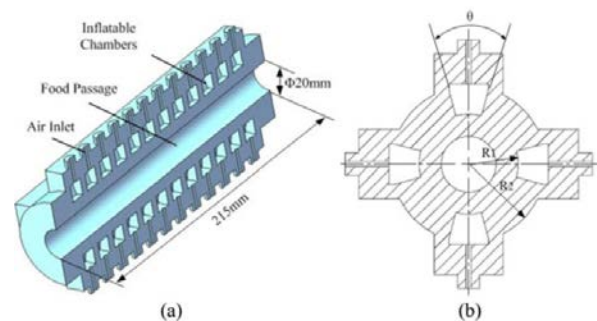


Figure 1(a) sectional view, with twelve layers of expandable chambers embedded along the food passage; (b) cross-section view.

This design employed a soft body actuator which is light weight and less likely to cause harm to human. However, the nonlinear characteristics of chamber deformation had made it difficult to control the peristaltic process.

B. Roller Based Mechanical Esophagus

An internal communication by Steven Dirven and Feijiao Chen to Professor Peter Xu had revealed a different concept for designing a robotic esophageal tract. Inspired by the biological esophageal actuation, this design emphasizes the continuous propagation along the conduit. Instead of a multilayer actuator design, a single actuation platform was proposed, as shown in Figure 2. The main interface between esophagus conduit and esophageal robot were six rollers that were free to rotate. They were connected to the hexagonal platform via six mechanical links, with each link being actuated towards the esophagus tube by pneumatic actuation.

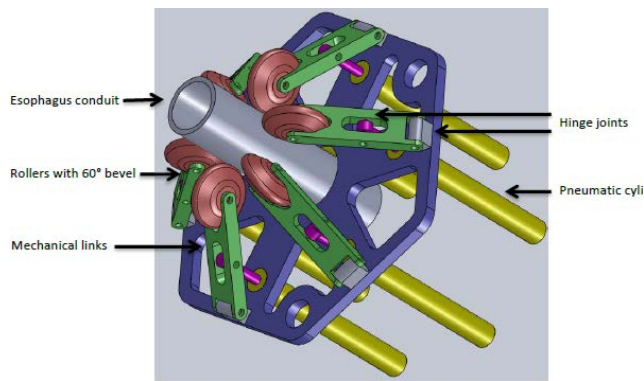


Figure 2 Concept for Single Platform Esophageal Peristalsis Actuator

When pressure is applied to the pneumatic actuators, the links bends down towards the platform, reducing the diameter of circle surrounded the six rollers, as depicted in Figure 3. The up and down traversal motion of the platform can be controlled by driving three separate screws in either clockwise or anticlockwise direction. Three threaded circular holes are connected to these screws which enables the platform to move along the esophageal conduit.

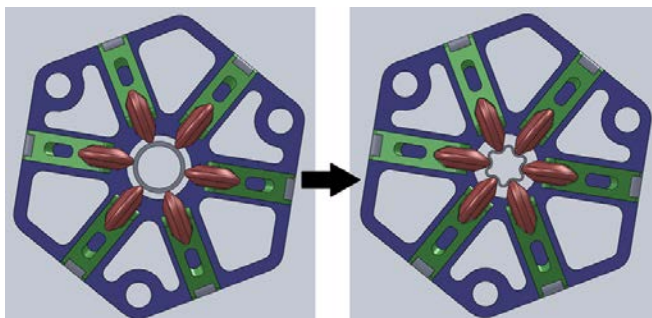


Figure 3 Contraction Simulation

Although such design was biologically inspired to achieve continuous motion, the edges of the rollers may cause compliance issue when interacting with the esophageal conduit. There is a risk of stretched esophagus as the platform travels down. From the control perspective, the three threaded mechanism must be perfectly synchronous otherwise the platform will become unstable and vibrates if the speed of three screws don't match. A further development has therefore become necessary.

C. Bowel Peristalsis Using Artificial Rubber Muscle

A research published in 2010 introduced a peristalsis robot which utilized artificial air muscle to imitate the intestinal circular muscle [7]. Figure 4 illustrates the components of a muscle unit. Each unit comprised of an air joint, a cylindrical tube and a chamber, which were separated by flanges at both ends of the artificial muscle.

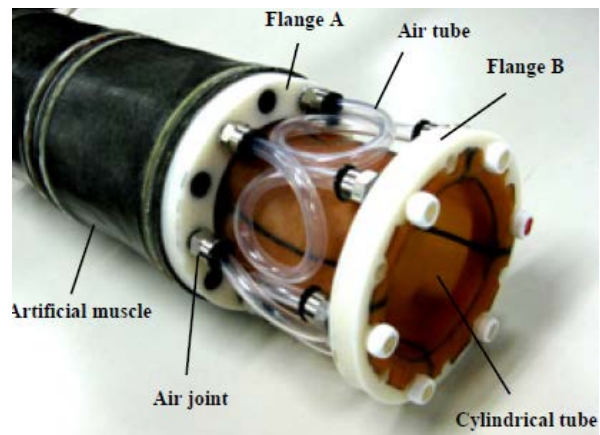


Figure 4 Sectional View of Artificial Muscle

When pressure is applied to the chamber via the air vent, the artificial muscle inflates and exerts force to the central cylindrical tube. The flexible tube will then contract in response to the external pressure. The motion pattern for bolus transportation was similar to the design in Fig.1. The motion can be divided into N state, where N equals to the number of air muscle units. Fig. 5 shows the schematics of a typical six-unit bowel peristalsis robot. Fluid or bolus can be conveyed from left to right by pressurizing two adjacent units in turn, starting from the left most units.

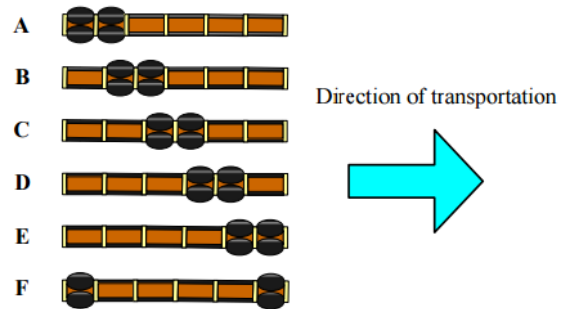


Figure 5 Schematic Diagram of the Motion Pattern

Both concepts in Figure 1 and Figure 4 have shared a lot of common characteristics, but the bowel peristalsis robot still differed from the other design in that the bowel peristalsis robot had enclosed air tube which made it more compact in size. The chamber of the bowel peristalsis robot was in circular shape, which resembled biological shape of human esophagus. However, unlike the four-chamber-multi-layer design in Figure 1, the bowel peristalsis robot had only one actuator in a unit, meaning that it cannot pressurize individual chamber to achieve certain actuation pattern.

III. CONCEPTUALIZATION AND SPECIFICATION

A. Limitations of Pneumatic Actuators

All of the three different design concepts discussed in Section II used pneumatic actuators, indicating that an air compressor must be used as the source of pressurized air. Use of air compressor and numerous air tubes (depending on the number of actuator units) would greatly compromise convenience and mobility, making it difficult to relocate these devices during operation. Air compressor is not as common as

electricity and the cost for purchasing an air compressor is relatively high. The limitations of pneumatic actuated robots determine that these concepts can only be used in lab or hospital environment. As a result, a novel electrical robot was designed to improve the mobility and cost effectiveness of traditional esophageal robots.

B. Vortex Inspiration

The friction between liquid and the internal wall of esophageal conduit is a key parameter determining the system efficiency and reliability. The higher the friction is the more power is consumed to push the liquid to one direction hence the material wears out quicker. If the liquid can self-induce a pressure to enable a faster travelling speed then the system's effort can be minimized.

The concept was inspired by the toilet flush design which induce a vortex to achieve faster fluid flow (Figure 6). Flushing water in a toilet is injected either in the clockwise or anticlockwise direction away from the center, creating a vortex with the core being near the outlet.

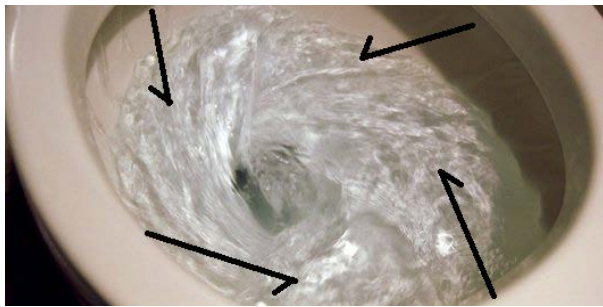


Figure 6 Toilet Flushing Illustration

According to the Bernoulli's principle, the rise of fluid speed is accompanied by a drop in fluid pressure, or decrease in fluid's potential energy [8]. The fluid speed in a vortex is the greatest in the center, hence the pressure is the lowest. This results in a negative pressure at the core, hence a downward suction force is created, as illustrated by Figure 7.

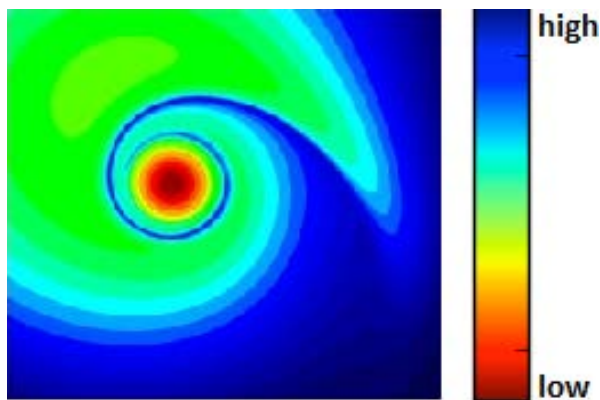


Figure 7 Pressure Distribution in a Vortex

It is therefore believed that if vortex is introduced in the esophageal conduit, the flow velocity of the vortex core can be significantly increased. In this research, the concept of vortices was utilized to improve swallowing efficiency.

C. Schematics of Vortex Swallowing Robot

The vortex swallowing robot mainly consists of a threaded female rotor, a threaded male rotor, two solenoids, two free rolling balls and an esophageal conduit, as shown in Fig. 8. The balls are free rolling inside the solenoid casings while the solenoid casings are fixed to the male rotor.

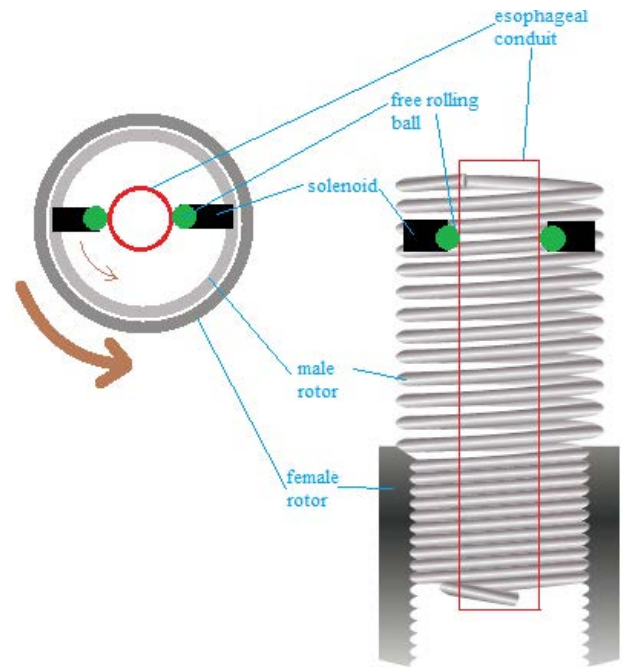


Figure 8 Overall Design of Vortex Swallowing Robot at Rest: Top View (left) and Front View (right)

When swallowing process starts, electrical power is applied to the coil inside the solenoid, pushing the free rolling ball out which then compresses the flexible esophageal conduit. Outer rotor and inner rotor simultaneously begin to rotate, but at two different speeds. Imagine if female rotor starts spinning while the male rotor's rotation is constrained, the male rotor and solenoids will slide into the female rotor housing. But they will not rotate. This is similar to tightening a nut to a bolt. On the contrary, if both rotors have the same angular velocity, the male rotor and solenoids will be free spinning in space with no longitudinal motion. Combining these two facts together, it was discovered that if the male rotor is instructed to rotate at a nonzero speed that is lower than the female rotor speed, the asynchronous motions of the two rotors result in both longitudinal motion and rotation, as depicted in Figure 9.

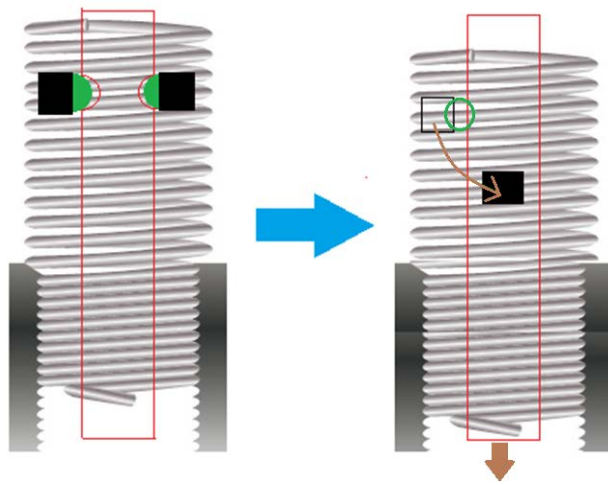


Figure 9 Combination of Transition and Rotation

The synergy of transition and rotation of the free rolling balls creates forces not only in the longitudinal direction, but also in the traversal direction (Figure 10). As a result, liquid is guided to travel in a spiral manner, creating a vortex inside the esophageal conduit.

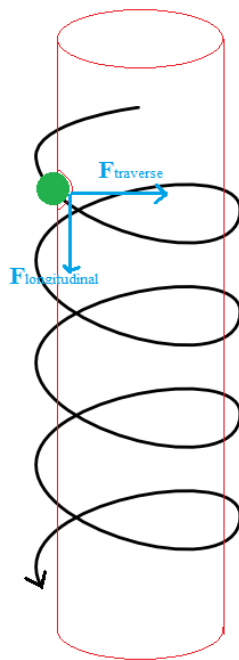


Figure 10 Trajectory of Rolling Ball Motion

IV. MECHANICAL DESIGN AND DEVELOPMENT

A. Motor Design

The aim of this project is to design a portable device. Ideally it can be powered from a 12V battery pack. Therefore a DC motor is selected to drive the rotors. Although the two rotors need to be driven at two different speeds, only one DC motor is used to minimize the cost and weight of the overall device. The speed differential is achieved by the introduction of a gearbox (Figure 11).

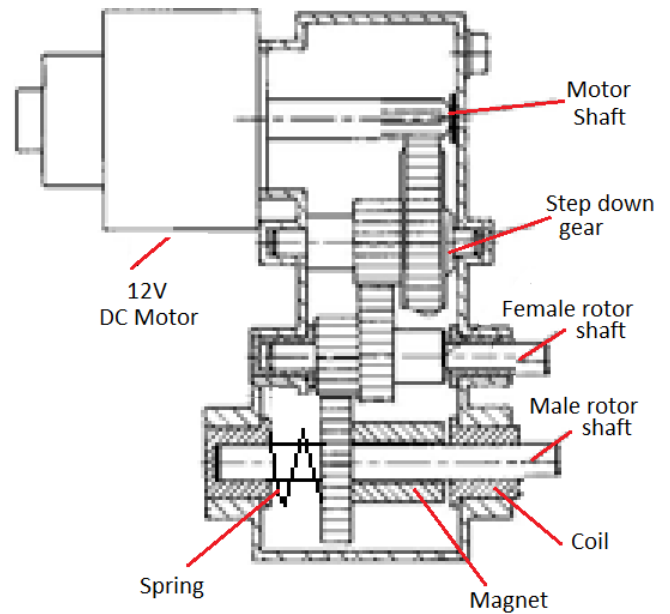


Figure 11 Dual Shaft Driving Diagram

The speed output of the female rotor shaft and male rotor shaft can be controlled by selecting the appropriate gear. There are two operation modes to choose from. In the first mode, the coil is magnetized. The coil will then generate an electromagnetic force that pushes the bottom gear to the left, disengaging male rotor shaft from the female rotor shaft. The normal force applied on the bottom gear also restricts the male rotor from rotating while female rotor is driven spin. In this mode, rolling ball travels vertically down in a straight line and the longitudinal speed reaches maximum.

In the second mode, the coil is fully discharged. The spring mounted on the male rotor shaft pushes the bottom gear to the right, allowing the gears to re-engage. The male shaft is therefore driven to rotate at a speed lower than the female rotor. And the rolling ball now follows a spiral trajectory as depicted in Figure 10.

B. Solenoid Design

The solenoids are the critical components that determine how far the rolling ball will press into the esophageal conduit. Each solenoid unit consists of a coil, a spring, a magnet plate and a free rolling ball, as shown in Figure 12.

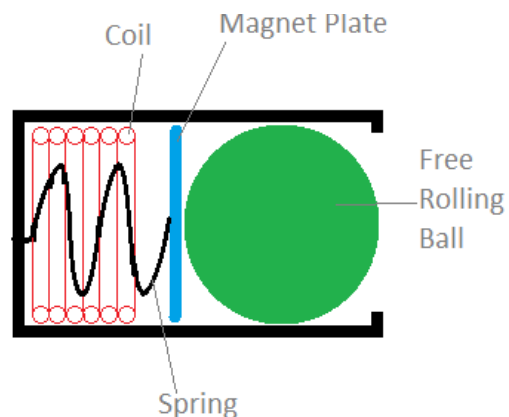


Figure 12 Cross-Sectional View of a Solenoid Unit

Figure 12 shows the natural state of the spring. When power is applied to the coil, a magnetic field is generated to repel the magnet plate, pushing the ball outwards. The amount of horizontal transition (how far the rolling ball shoots out) can be adjusted by varying the current supplied to the coil.

C. Future Applications

Researches in 2001 and 2008 have revealed that modified food and drinks can improve the esophageal performance on patients diagnosed with dysphagia [9],[10]. Nevertheless, the in vivo swallowing process has only been poorly understood, causing barriers in food rheological properties study which can help to alleviate the dysphagia symptoms[11].

Vortex esophageal robot is a multi-functional device that is low cost with excellent mobility. It can source power from a 12V DC battery pack which enables it to be carried around for education and demonstration purposes. When the first mode is selected, this design is virtually identical to traditional esophageal robot, which can provide the insight of bolus flow to healthcare workers to assist them decide the rehabilitation plan.

As this device is relatively low cost and the power source is readily accessible. It can be further developed into a commercial product that is available to the dysphagia population. This device can be purchased from a healthcare specialist, who is able to preset the parameters to ensure the simulator can mimic the patient's esophageal configuration. If a patient wants to intake foods and drinks that are not included in the list doctor's recommendation, this device can act as a perfect tester to give indications of whether it is safe to intake such foods or drinks, reducing the risk of suffocation.

When this device is switched to the second mode, it can be used as a peristaltic pump to convey liquid and liquid-solid mixture. Similar devices have been developed using pneumatic air muscles [7],[12], electrostatic actuators[13], colloidal systems[14] and piezoelectric actuators[15] from other previous researches, but the sizes of these devices constrained the entries into a more confined space. The battery-powered esophageal robot is the perfect conveyance in these areas. With vortex technology, it can be expected that high viscosity liquid and liquid-solid mixture can get through the passage faster. Typical areas of industrial applications include earthworks, mining and civil engineering where a mixture of rocks, soil and water need to be transferred.

V. CONCLUSION

The pilot study of a vortex esophageal robot has successfully demonstrated the feasibility of such concept. The main advantages of this device include portability, compact in size and relatively low cost. Control algorithm of spring-damper system is more simple and predictable compared to nonlinear pneumatic actuators. However, use of threaded driving system compromises the flexibility of the device. It cannot be bent or twisted to get through certain terrain. In the future, research work will continue to finish the

electronic interfacing circuit and material selection, after which the first prototype can be built to carry out product validation.

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Proposal for a Wearable Device for Lateral Movement of Jaw

Zhao Jian

Abstract— This paper presents the development of a wearable device for rehabilitation of temporomandibular disorder. Through improvement to the mechanism and additional actuators and control system for the wearable device, which was only for open and close, forward and backward motion in the sagittal plane, the lateral movement could be implemented. At the same time, sensors are used to collect data for the trajectory of the movement and the safety of the patients.

I. INTRODUCTION

The temporomandibular disorder (TMD) could result from the problems with the mandibular joints, mastication muscles, mandibular bone, and central nervous system. However, through non-invasive reversible therapy, the symptoms of TMD could be relieved because of the reversibility of the symptoms [4]. According to the reason of the disorders, the neuromuscular dysfunction and musculoskeletal factors are two kinds of the potential diagnosis of TMD [5]. For the musculoskeletal factors, it has been proved that continuous exercise is effective to the relief of the symptoms through improving the metabolism in the muscles and joints [6]. Besides, the cortical cells in the impaired central nervous system could be renewed via effective exercises, which means that exercise could be applied into the neuro-rehabilitation for the masticatory system [7], [8].

After realizing the benefit of the exercises for the masticatory system, people used some methods to do the exercises. Traditional methods for opening exercises were

completed via manual finger movement and stacked tongue depressors [9]. But not only were there methods inconvenient, but also were the results unideal for long-term physical therapy.

There have been some robots for the rehabilitation of temporomandibular disorder, such as WY series robots. However, the inaccessibility for patients makes the requirement for an ambulatory device because of the intensive exercise.

Therefore, a wearable and head-held device has been developed, which is shown in Figure 1. However, during the design of this device, the three-dimensional movement of the jaw is simplified to moving in two-dimensional sagittal plane. So it could only finish the mouth open and close, forward and backward movement.

In this paper, mechanism improvement is carried out to increase the lateral movement, based on the model in Figure 1. The frame is divided into the fixed part and movable part, which could complete the lateral movement according to the designed trajectory. Meanwhile, sensors are used to detect the position of the mandibular condyle and then the data will be analyzed for the control system. The control system could make the lateral movement though the up and down, left and right movement of the movable part.

This improvement on the device broadens the applicable range of the wearable device, which could not only complete the accessibility, but also increase the degrees of the freedom. This is meaning for the rehabilitation of temporomandibular disorder.

II. RELATED WORK

A. The masticatory system

The masticatory system comprises the maxilla and mandible, as shown in Figure 2. The maxilla is fixed and a part of the skull. The mandible is attached to the skull by muscles and temporomandibular joints (TMJ) which are also the rotation axis of the mandible. The central neural system (CNS) controls the movement of the mandible.

The TMJ is the joint between the condyle of the mandible and the temporal bone of the skull, as shown in Figure 3. An articular disc resides in between temporal bone and mandible and separates them. At the same time, the articular disc could absorb the shocks when people chew and avoid the injury to the TMJ. The ideal human mandible has 3 degrees of freedom (DOF), which are mouth open and close, forward and backward, and a lateral motion.

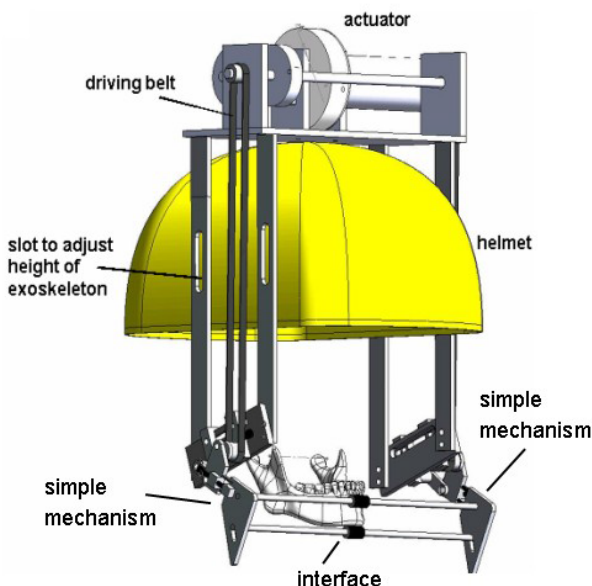


Figure 1. The model of the wearable with the jaw [4]

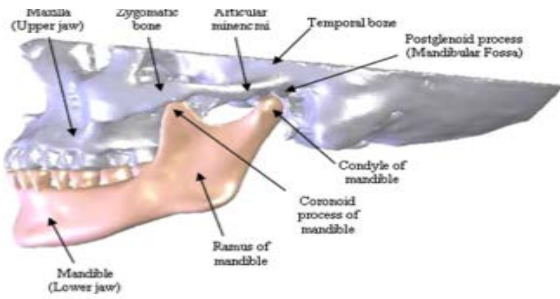


Figure 2. Bones of skull and mandible in lateral view [1]

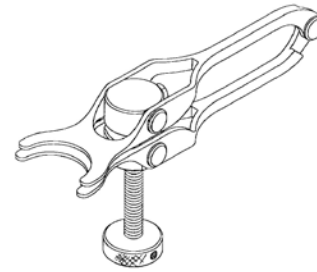


Figure 5. Assembly diagram of TMJ opening exerciser [6].

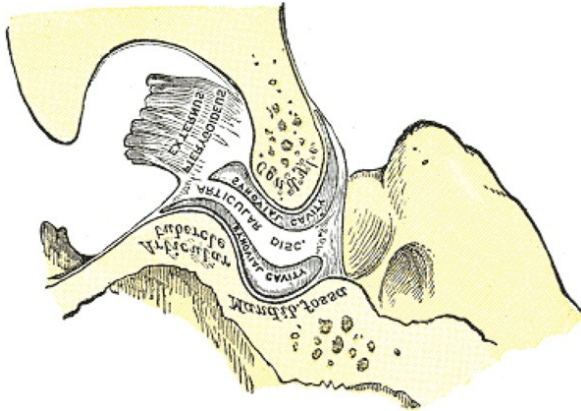


Figure 3. Sagittal section of the temporomandibular joint [2]

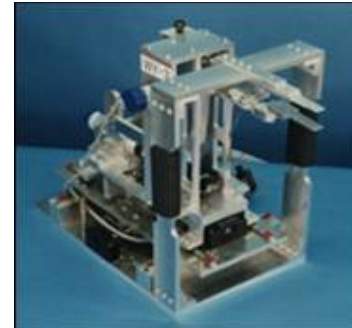


Figure 6. WY-3 robot [10]

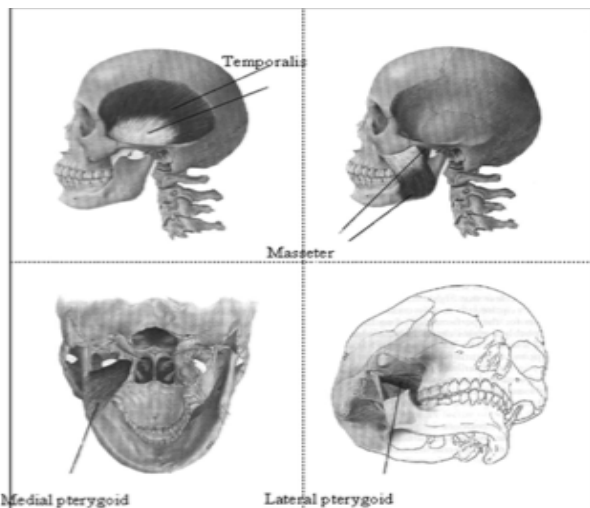


Figure 4. Masticatory muscles [3]

The mastication system is driven by a group of masticatory muscles which contain masseter, temporalis, medial pterygoid, lateral pterygoid and digastric [3]. Figure 4 shows the former four kinds of the muscles.

B. Rehabilitation devices

As mentioned above, the temporomandibular disorder (TMD) could result from the problems with the mandibular joints, mastication muscles, mandibular bone, and central nervous system. And continuous exercise is very meaningful for the rehabilitation of TMD.



Figure 7. The jaw training with WY-6 robot [10]

Several devices have been made for opening and closing the TMJ exercises, such as screws or cones with enlarging diameters, elastic traction, hydraulic passive motion devices and “Therabite” jaw motion rehabilitation system. But there were some problems including poorly distributed force, creating pressure sores, lack of short-term durability, required preliminary opening and high cost [6]. A new type of TMJ opening exerciser, shown in Figure 5, could overcome these disadvantages for patients with TMJ ankylosis or hypomobility.

However, these simple devices could only complete the opening and closing the TMJ exercises and could not do the exercises for other degrees of freedom.

Since 1995, WY series robots have appeared for the training of jaw disorder patients [10]. The robots were developed continuously, with improving the functions and

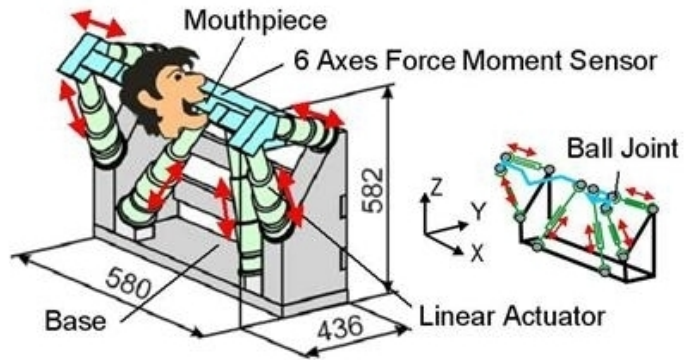


Figure 8. The WY-5 robot and the mechanism [10]

increasing the number of the degrees of freedom. In 1997, WY-3 (shown in Figure 6), a 3-DOF treatment robot for jaw disorder person, was developed with master-slave system and could complete opening and closing training. The most advanced robot is WY-5 and WY-6 (shown in Figure 7) with a 6-DOF parallel mechanism between 1998 and 2004.

WY-5 robot is shown in Figure 8. The machine's 6-DOF mechanism is made up of ball screws which are actuated by linear motors. The upper mouth piece holds patient's upper jaw and patient's lower jaw is moved accordingly via the movement of parallel link mechanism. Compared with conventional way using mouth gages that can only perform 1-DOF movement which is opening and closing the mouth, the robot is more effective. After development, the lateral movement training could also be completed via this robot [11]. At the same time, EMG feedback monitoring system was added into WY-5 treatment robot. Using this system, the doctor can monitor EMG feedback in patient's jaw during the treatment process, which increases the effectiveness of treatment. The tele-training system for WY-5 treatment robot has been also developed, which upgrades the robot capability to do treatment even if the doctor is in distant place [10].

Although the WY-5 robot has many advantages, the inaccessibility makes it not conducive to the rehabilitation of the neurological temporomandibular disorders for intensive exercise required. Therefore, a wearable and head-held device has been developed. The whole system with the jaw is shown in Figure 1. In this design, the three-dimensional movement of the jaw is simplified as moving in the two-dimensional sagittal plane. It is based on a four-bar linkage, which includes the crank, coupler, follower and ground, as shown in Figure 9. The ground link and coupler link whose length varies between 30mm-40mm, and 30 mm-50mm implement the adjustability of the linkage. Different lengths of the ground and coupler could lead to different trajectories of the incisor point [4].

III. CONCEPTUALIZATION AND SPECIFICATIONS

A. Specification

The trajectory of the incisor point (IP) could describe the dominant movement of the jaw [4]. Figure 10 shows the lateral movement of the jaw. The lateral movement is a rotary motion around the left or right rotation center (temporomandibular joint). The left lateral movement is a rotary movement around the left rotation center and similarly the right lateral movement is a rotary movement around the right rotation center [11]. From the Figure 10, we could see that trajectory of the left lateral movement is an arc which the combination of the movement towards the left and movement towards the top. The trajectory of the right lateral movement is an arc which the combination of the movement towards the right and movement towards the top. By contrast, when the jaw moves from the left position to the center position, the movement is the combination of the movement towards the right and downward movement. When the jaw moves from the right position to the center position, the movement is the combination of the movement towards the left and downward movement. For a healthy person, the trajectories are approximately symmetric on both sides. However, many temporomandibular disorders patients' jaw could not move symmetrically or could not move at all.

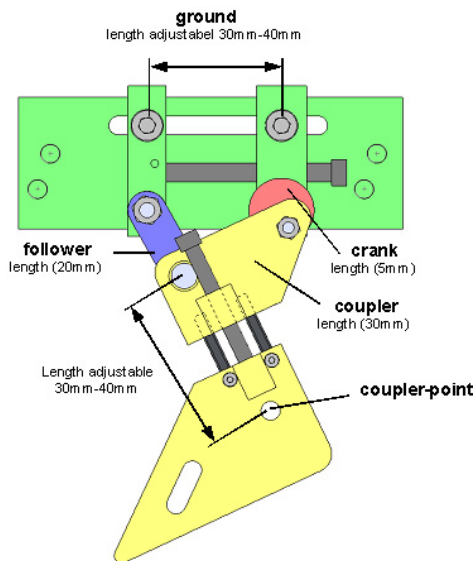


Figure 9. 3D model of the linkage [4]

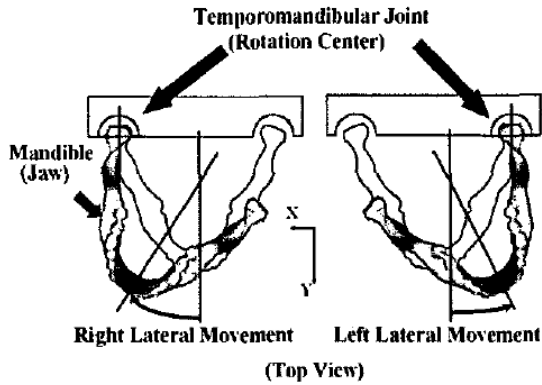


Figure 10. The lateral movement of the jaw [11]

In order to make the device used for the lateral movement, it should move as the trajectory of the movement of the jaw. Therefore, it could complete the up and down movement, left and right movement.

At the same time, it could supply enough force to drive the jaw for the lateral movement. When we open our mouth to some degree, it is easier to complete the lateral movement than that when we close the mouth fully. So the device must have the ability to open the mouth and fix the jaw at some degree.

Other requirements include that the device must be adjustable for the different sizes of jaw and head, that the device should make the patient comfortable as much as possible. For a wearable device, it should be lightweight to make it accessible for long-term exercises.

The most important aspect is the safety of the patient. In order to avoid the device moving over the limit of the patients' mandibular movable area, the safety program will be applied in the computer to limit the movable area of the device.

For the wearable device that is shown in Figure 1, it could open the mouth to some degree and fix it at some degree. Therefore, how to make it move leftwards and rightwards

should be considered.

B. Mechanism

In order to make the device have more degree of freedom, the whole device is divided into two parts, the fixed part and movable part. The simplified mode of one part above the head is shown in Figure 11.

The fixed part, which is relatively stationary to the skull, comprises:

- A helmet.
- A fixed frame.
- The joint between the helmet and the fixed frame. It is adjustable in order to meet the demands of different people, because there is difference on the head size for different people. The joint contains the screw structure which is convenient to adjust.

The movable part includes:

- The plate belonging to the movable part. On the plate there is a slot which allows the movable part to move up and down, left and right, so that the lateral movement could be completed.
- The actuator which is on the movable frame, as shown in Figure 1. It could drive the system to complete the opening and closing training.
- Four actuators which are controlled by a computer and drives the system for lateral movement.
- Two four-bar linkages, as shown in Figure 1, which could make the incisor trajectories for the two-dimensional movement in the sagittal plane.
- The chin-connection bars which connect the two four-bar linkages.
- The movable frame. One end is connected to the plate, the other end is connected to the actuator which could make the system complete the lateral movement.

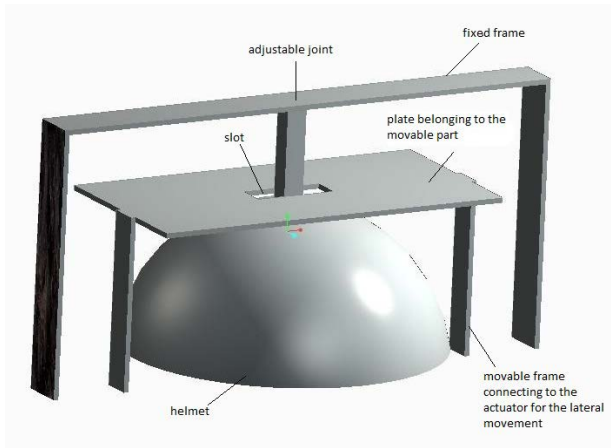


Figure 11. The simplified model of the helmet part

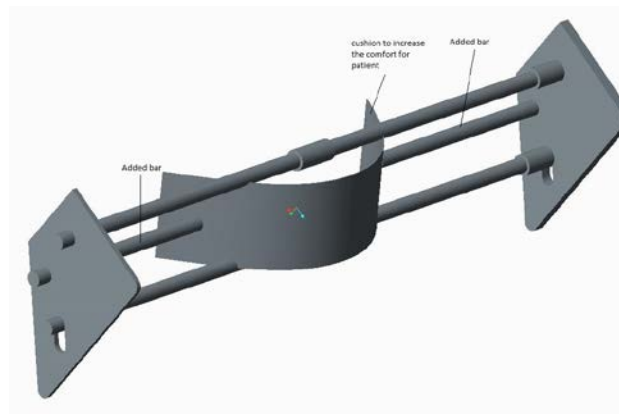


Figure 12. The improved chin-connection bars with a cushion

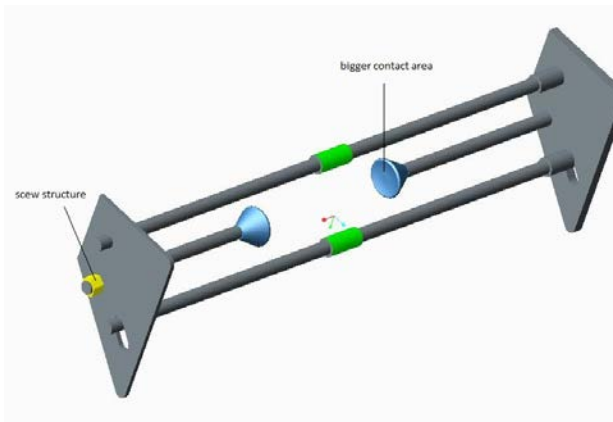


Figure 13. The bars picture showing details

The combination of the fixed part and movable part make it possible to complete the up and down movement, left and right movement. Besides, the adjustable function for the different sizes of head has been solved via the adjustable joint between the helmet and the fixed frame.

In order to make the chin-connection bars drive the chin to move laterally, the chin-connection bars should be improved.

The improved bars are shown in Figure 12. Another two bars, which are added into the system, are connected to the two plates respectively. The two added bars could increase the driving force for the lateral movement. In order to make patient feel more comfortable, there is a cushion added at the position of the jaw. The cushion is connected to all the bars so that the force worked on the cushion is enough and more points of application could make the patient not feel too strong at one point. The cushion surface that contacts the jaw could be added with a piece of sponge so that the buffering of the sponge could increase the comfort for the patient.

In order to show other details, Figure 13 is shown. One end of the added two bars is connected to the cushion. The contact area could be increased, so that the intensity of the pressure worked on the cushion could decrease. Meanwhile, the contact surface of the bars could be made into arc-shape which is similar with the shape of jaw, so that the effect of the driving force is more significant. This also could make patient feel more comfortable. The other end of the added two bars is connected to the plates with screw structure, which makes the length of the bars adjustable. This is important because different people have different jaw sizes. In order to make the full contact between the jaw and the cushion, the added bars should be adjustable. Besides, the cushion should be made of soft materials so that it could be adjusted with the bars to suit the different lateral sizes of different patients. The lowest bar in Figure 13 is also adjustable for the different sizes of jaw.

Therefore, the adjustable function could be completed via the adjustable bars. Meanwhile, the requirement of the comfort for the patient could also be accomplished by the cushion, bigger contact area and arc-shaped contact surface.

IV. MECHATRONIC DESIGN AND DEVELOPMENT

A. Sensor

In order to keep the patient safe, laser distance-sensors could be attached on the fixed frame, as shown in Figure 14. The position of the sensors could be adjustable, so that they can suit different sizes of different people.

At first, we need to set a limit in computer, which means when the data from the sensor exceed the limit, the jaw may move over the limit of the movable area and make damage to the patients. This limit should be conservative, in order to reduce the risk of damage. During the lateral movement, the sensors are used to measure the position of skin at mandibular condyle and then the data are delivered to the computer. If the position data is smaller than the limit we set, the actuators could move continuously, or the actuators will be stopped and the program that makes the jaw move to the initial position will operate. The safety procedure is shown in Figure 15.

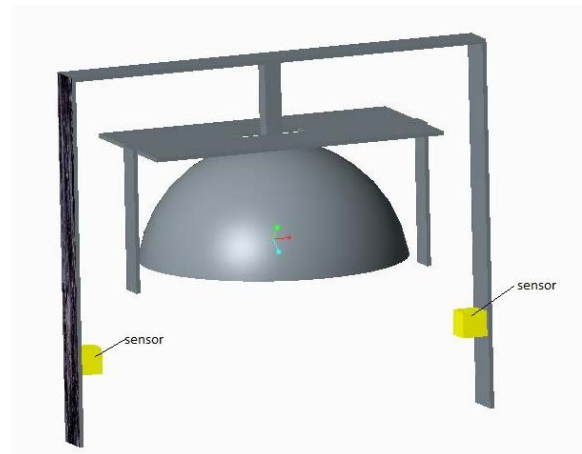


Figure 14. The position of the sensors

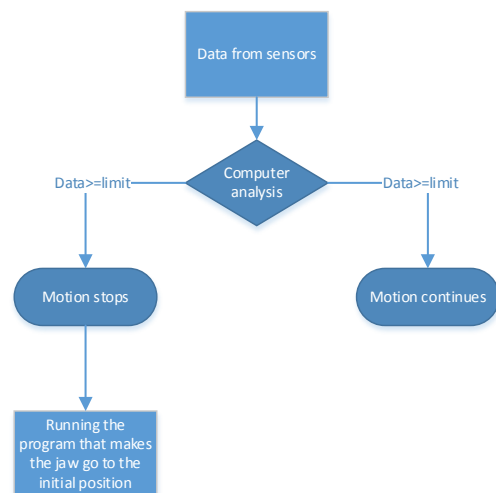


Figure 15. The safety procedure

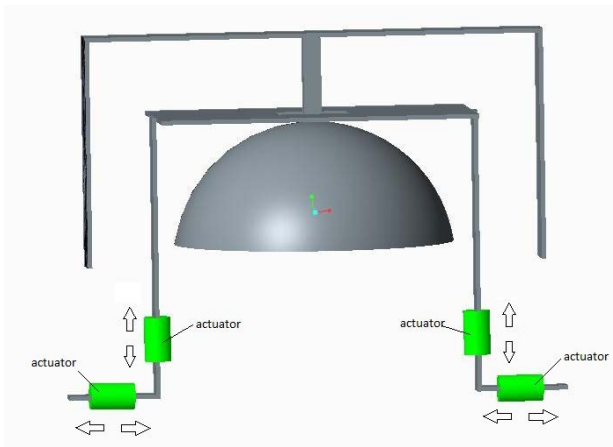


Figure 16. The position of the actuators

Another function of the sensor is to detect the initial position of the lateral movement. When the mouth opens to some degree via the four-bar system and then the jaw is fixed at this degree, the sensors deliver the data, which represent the initial position of the lateral movement, to the computer. These data will be applied to the motion control.

B. Actuation

As mentioned above, the lateral movement is the combination of up and down movement, left and right movement. Therefore, we could install several linear actuators that could implement these movements.

As shown in Figure 16, four linear actuators are installed on the movable frame. Two actuators on the vertical frame could make the movable frame move up and down, the other actuators on the horizontal frame could make the movable frame move left and right. These actuators are all under control of the computer to complete the combination of the movement. The movement of the actuators should be smooth so that the patient will feel comfortable.

C. Motion control

After the mouth opens to some degree via the four-bar system, the trajectory of the lateral movement is similar with the trajectory shown in Figure 17. We can design a program to control the four actuators that could control the lateral movement. The procedure of the program is shown in Figure 18.

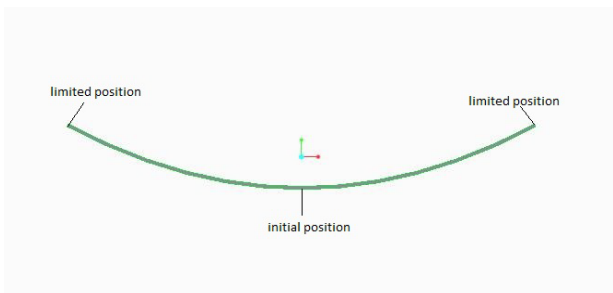


Figure 17. The trajectory of lateral movement

There is a limited position for the lateral movement both on the left and right side which we need to set in the program. This value is different from the value that we use to compare with the data from sensor. That means in the program, we limit the movable range directly. Whether the data from the sensors reach the limit or the movement gets the limited position we set in the program, the movement will stop. These two limits form the double safety for the movement.

After the mouth open to some degree, the sensors record the initial position. Then the leftward and upward motion begin, in order to complete the left lateral movement. As mentioned above, whether the data from the sensors reach the limit or the movement get the left limited position we set in the program, the movement will stop and the rightward and downward motion will begin. When the jaw reaches the initial position, the motion will stop. The left half part of the lateral movement has been finished after this step. Then the rightward and upward motion will begin. Whether the data from the sensors reach the limit or the movement get the right limited position we set in the program, the movement will stop and then the leftward and downward motion will begin. When the jaw reaches the initial position, the motion will stop. The right half part of the lateral movement has been finished after this step.

If there is no stop order, these steps will be implemented again. If the stop button is pressed, the circulation will stop, which means the exercise will stop.

In order to complete the trajectory in Figure 16, the velocity of the actuators for the left and right movement is different from the velocity of the actuators for the up and down movement. Specifically, the former is bigger than the latter. The specific value should be calculated according to the actual distance of the movement. There is some tiny difference for different people in the trajectory, so we can set up a database for the velocity that we can transfer, in order to control the lateral movement better.

At the same time, we need to consider about the compensation. For the actuators for the leftward and rightward movement, the friction should be considered. For the actuators for the upward and downward movement, because the motion should overcome the gravity of the movable part, the friction and gravity should be considered.

V. CONCLUSION

Through the consideration of the above aspects, the lateral movement could be completed by the wearable device. The parameters should be considered carefully during the process of the design.

However, when we apply the sensors and actuators into the design, the computer and other electronic devices will be used, which means the overall weight of the whole system will increase. Therefore, the accessibility of the device will decrease. When we choose the materials, the materials should be as light as possible in order to resist the negative effect of the heavy device.

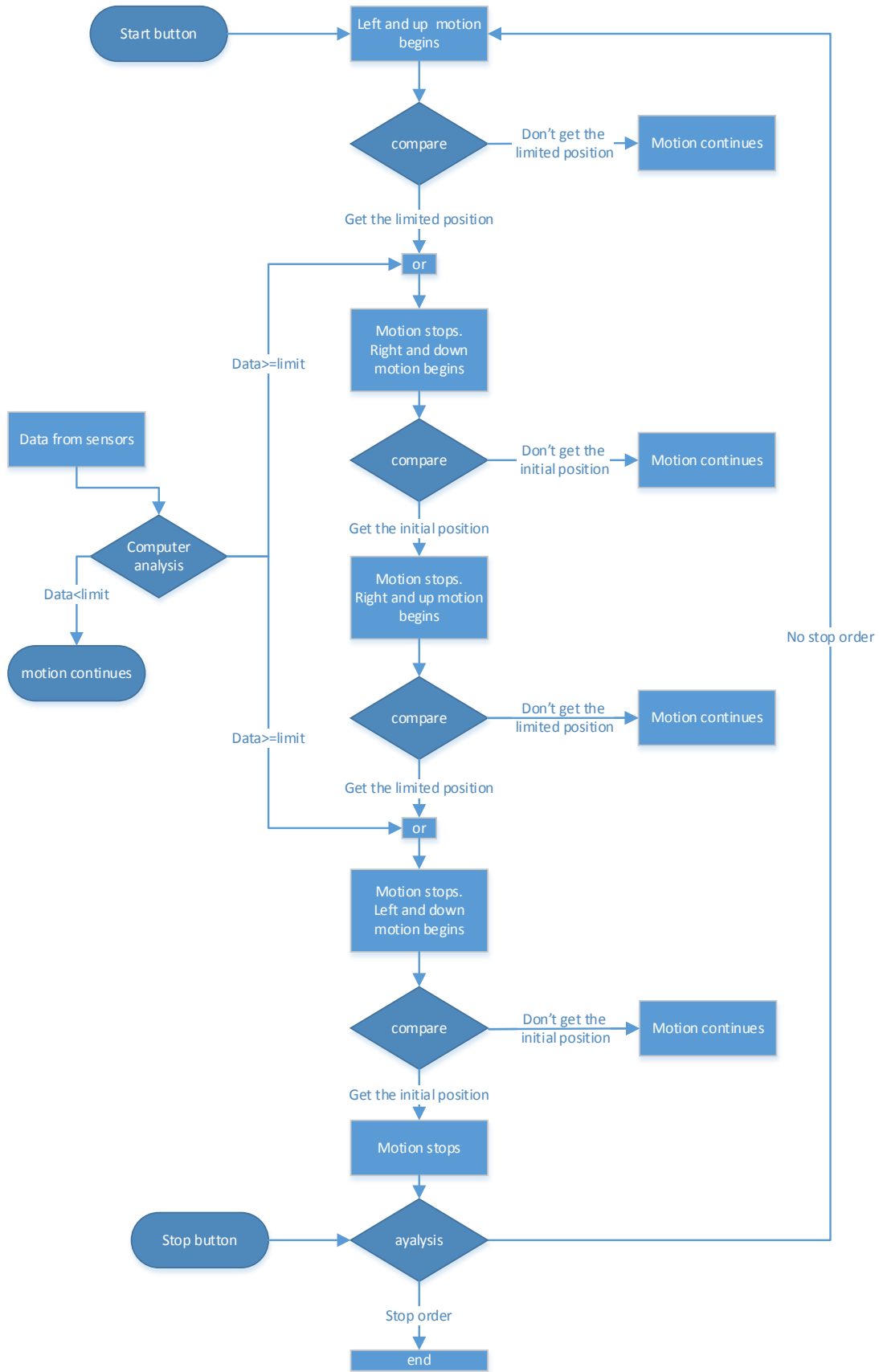


Figure 18. The procedure of the program for the lateral movement

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Design and Evaluation of a Safety-Critical Robotic Exoskeleton for Rehabilitation of Temporomandibular Disorder

Zhong Xuren

Abstract—Temporomandibular disorder (TMD) is a group of dysfunctions in human masticatory system which can cause muscle stiffness and masticatory disability, and result in a decrease in the mouth's range of movement (ROM). This paper describes a preliminary design of a robotic exoskeleton for rehabilitation of the TMD. It can apply three degree of freedom (DOF) movement on human jaw, simulate real masticatory movement, implement exercise treatment and biofeedback treatment at the same time, and also achieve real-time monitoring and assessment. A series of safety strategies are applied in the system through a safety analysis technique. Then several evaluation methods are described by considering acceptance factors and ethical issues for this kind of robots.

I. INTRODUCTION

Temporomandibular disorders covers a wide range of conditions. Around 50% to 70% of people will show some signs of a TMD in their life, and 20% of these signs will turn into symptoms, such as facial pain, jaw joint pain and restriction of the mandibular movement. [1] As multi-disorder is very common in TMD patients, this project aimed to design a multi-therapy robotic exoskeleton for rehabilitation of TMD. A real-time multi-examination assessment was also under consideration in order to simplify the assessment process. This paper introduced a safety analysis method and developed a safety-critical system. After that, I briefly discussed acceptance factors and ethical issues in regard to this kind of rehabilitation robot, and found several methods to evaluate them.

II. LITERATURE REVIEW

A. Masticatory system & TMD

The masticatory system is very vital in human body as it is the first part of digestion system for taking into food. It consists of the temporomandibular joints (TMJs), intra-articular discs, mandibular muscles and occlusion as shown in Figure 1. [1] Put simply, the TMJ is the two-sided

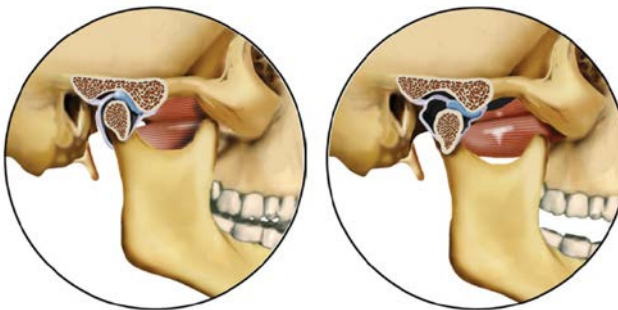


Figure 1. Normal closed and open condyle and disk position [2]

articulation between the upper and lower jaws. [3] The intra-articular disc covers the whole contact area between the joints to absorb impact energy. This system is unique in the human body as the TMJs are paired, which means that stimulus on one joint can cause a 'knock-on effect' in another joint. [1]

TMD is a group of dysfunctions in the masticatory system that causes joint articular disorders and masticatory muscle disorders. [4] There are three main clinical examinations to evaluate the TMD patients: range of motion, TMJ noise, and TMD palpations. [5] According to the definition, TMDs can be summarized into two main diagnostic categories:

- TMJ articular disorders: disc displacement disorders, dislocation, inflammatory disorders, osteoarthritis, ankyloses, and fracture.
- Masticatory muscle disorders: myofascial pain, myositis, myofibrotic contracture, centrally mediated myalgia, local myalgia, and neoplasia.

Since TMD has many etiologic factors, a number of therapies have been shown to have a positive impact on rehabilitation. [5] For instance, continuous passive motion (CPM) has valid effectiveness in pain elimination and ROM restoration. [4][6][7] Other than the CPM exercise, treatments involving EMG biofeedback can also improve the effectiveness. [8] During the biofeedback treatment, patients are able to observe how different relaxation skills can change their muscle tension, and learn to relax their muscles and reduce symptoms. [5]

B. Exoskeletal Robot

Exoskeletal robot, also called wearable robot, is a person-oriented robot. [9] It is one kind of bio-mechatronics. A typical mechatronic system contains mechanical system, electronic system, control system, and computers. [10] While the human being plus the 'bio' part to the mechatronic system, the basic components for a bio-mechatronic system are the human subject, stimulus or actuation, transducers and sensors, signal conditioning elements, recording and display, and also feedback elements, which build a complete feedback system.

- Sensors and transducers are used to monitor the subject's bio-signals, such as limbs movements and body temperature, and then convert them into electrical signals in this system.

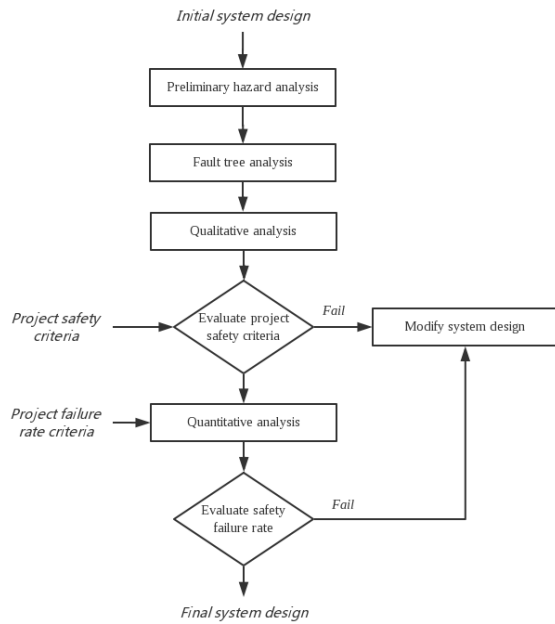


Figure 2. Safety analysis flow chart [13]

- Stimulus or actuation can have effect on human subject, which includes electrical stimuli, an audio tone, a source of light, and so on. [10]
- Signal processing elements are used to modify the electrical signals from the sensors. It usually contains amplification and filtering. [10]
- Recording and display elements are necessary in most cases, which can store useful data for later use and display important parameter for real time monitoring.
- Feedback elements are key in the closed-loop control systems. By comparing the output data from sensors and desired effect, it can control the input.

C. Safety Strategy

Compared with traditional robot, safety is more important for exoskeletal robot as it has direct interaction with human body. For rehabilitation robotics, safety should be the highest priority as patients are more vulnerable than others. However, most of the rehabilitation robotics for TMD are insufficient to protect patient. [11][12][4] Although they have implanted safety components, like emergency stop and so on, they did not systematically analyze the safety strategy.

Roderick and Carignan introduced a safety analysis method to develop safety-critical rehabilitation robots (Figure 2). [13] They combined preliminary hazard analysis (PHA) and fault tree analysis, which can enumerate the hazards, determine the fault sequence both qualitatively and quantitatively. They defined a failure as ‘an abnormal occurrence’, a fault as ‘a higher- order event caused by one or more failures’, a hazard as ‘a system state and other environmental conditions that inevitably leads to an accident’, an accident as ‘an undesired and unplanned event that results in a level of loss, in this case, injury to the patient’, and safety

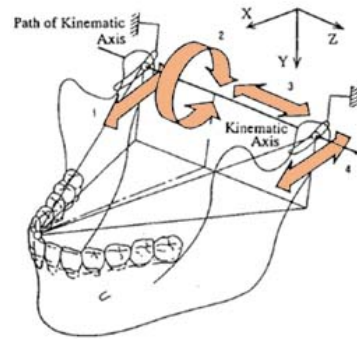


Figure 3. Jaw movements of three DOFs [14]

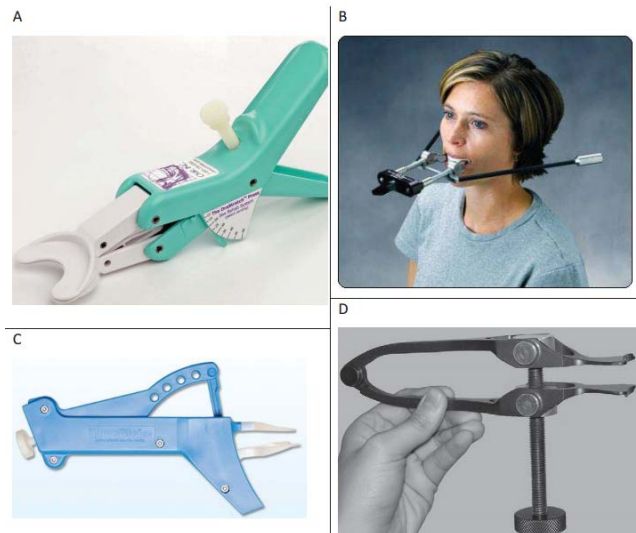


Figure 4. Traditional devices [4]

as ‘freedom from accidents’. Meanings of these safety-related terms used in this paper based on these terminologies.

D. Previous TMD Rehabilitation Robots

Human jaw involves three degree of freedoms (DOFs) as shown in the Figure 3. They are open and close movement, forward and backward movement, and left and right movement. Traditional devices for rehabilitation of TMD can be generally called jaw exercises, which are developed to improve the ROM of mouth. In Wang’s paper, four commercialized devices were illustrated, including OraStretch™ Press, Dynasplint, Therabite, and an unnamed device using a power screw for opening the mouth, as shown in Figure 4. [4] Generally, this type of products can provide a proper guidance by passively forcing patient’s jaw in one DOF. They are usually operated by the patient or clinicians in order to apply desired force, velocity and ROM manually. Most of these devices contain changeable or adjustable parts which provide an adaptable guiding path for various applications. Case studies on the efficacy evaluation have proved the effectiveness of the jaw exercises in patients with TMD as well as the post-operative phases of TMJ. [4][15][16]

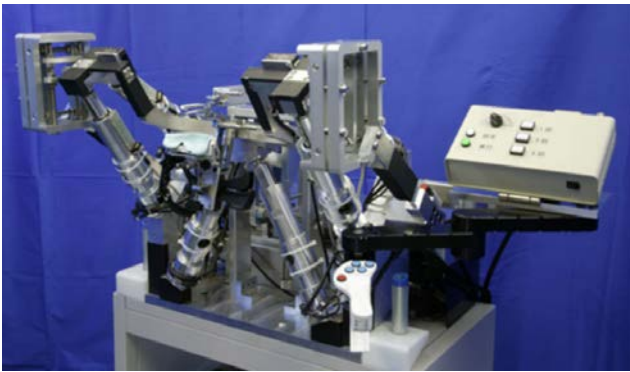


Figure 5. WY-5 Jaw Training Robot [14]

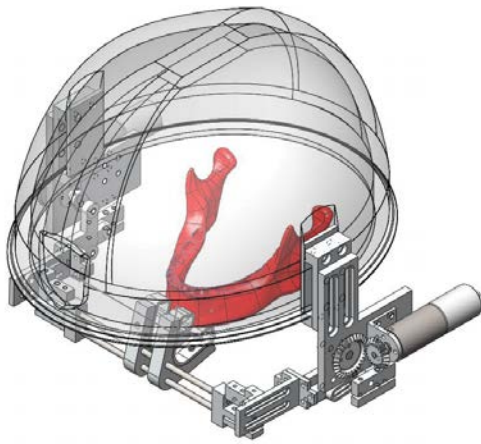


Figure 6. Wang's training robot [4]

Takanobu et al. developed a series of WJ (Waseda–Yamanashi) robots for the jaw movement training. [11][12][17] Xu et al. gave a brief summary to the development of the robots. [14] According to the summary, the overall development can be divided into four phases.

- Two DOFs: Human jaw involves 3 DOFs. Traditional devices can only provide 1-DOF movement (opening and closing) for the rehabilitation of TMD. It was the first time that the robot achieved the 2-DOF movement (additional forward and backward movements)
- Three DOFs: 3-DOF movement was achieved (additional right and left movements), which perfectly corresponded with human jaw's 3-DOF movement.
- EMG: The EMG sensors were implemented in the robot for the purpose of clinical trials.
- Mastication movement: The robot was able to mimic human's mastication movement.

However, this series of robots were very bulky (Figure 5). Wang designed a novel wearable assistive device for TMD rehabilitation (Figure 6). [4] Although it could only achieve 1-DOF movement considering limited operation space around the head, it significantly reduced the weight of the robot, and

made itself wearable for human by using four-bar linkage structure.

E. Literature Summary

Since multiple disorders are very common for TMD patients, it's important for a rehabilitation robot to cover as many disorders as possible. Considering robot's advantages and limitations, I decided to design a robot which can provide the CPM therapy and the biofeedback with relaxation therapy. With a combination of these two therapies, it is able to cover most of the TMD patients. Even for those fracture and neoplasia patients, it can be used as a post-operative treatment. In order to simplify the assessment process, the robot is also designed to provide real-time assessments of the ROM and the TMJ noise. The safety analysis method can be applied during the system design. However, the quantitative analysis could not be done due to lack of historical or experimental data.

III. CONCEPTUALIZATION AND SPECIFICATIONS

During the design process, six general requirements: namely, high safety level, high treatment effect, real-time assessment, easy to use, high comfort level, and low cost were considered. The whole system is divided into four sub-systems, and each system had its own sub-requirements. They were the mechanical system, electronic system, microcomputer, software-based control system.

A. Mechanical System

The sub-requirements for the mechanical system are: sufficient rotation angle, sufficient volume, no collide with itself, sufficient range of movement, suitable motor, strong material and structure, light weight, round surface characteristics, covers for protection, manual override switch, simple to worn, soft attachment, simple structure, high power-torque ratio, economical material, high manipulability, and high wear ability.

Considering the sub-requirements, this mechanical system should be wearable by various human subjects. According to Diffrient & Tilley, 97.5% male adults' head has a dimension smaller than $210*165*235 \text{ mm}^3$ (Length*Width*Height); 97.5% female adults' head has a dimension larger than $185*135*200 \text{ mm}^3$ (L*W*H) in the USA. [18] Firstly, the container should have a space area larger than $215*170*240 \text{ mm}^3$ (L*W*H), considering wider application. Secondly, the adjustable attachment on subject's head should be able to attach a head with a dimension of $170*120*185 \text{ mm}^3$ (L*W*H), considering pediatric patients. Besides, this exoskeletal robot should be easy to put on and off.

The body part of the mechanical system was developed to generate the trajectory reproduction. There are several methods to design this part: four-bar linkage, cam-linkage mechanism, auxiliary joint and robotic manipulator. [4] Although robotic manipulator has a bulky structure and heavy weight, it can generate multi-DOF movement. And compared with other methods, it can update its trajectory in the microcomputer without changing the mechanical structure. The maximum permissible weight Tobe carried on the head by a healthy male adult is 30 kg when working. [19] Considering female patient and wearing comfort, the limited maximum weight of this system should less than 8 kg; the total weight of

the whole system should be less than 10 kg. Although the minimal force to open the jaw by healthy people is less than 5N, the force applied to the jaw to execute rehabilitation exercise is between 10N – 30N. [20] For wider application, the robotic manipulators should be able to generate a force between 5N – 50N.

Although we generally need two trajectories for the incisor point (IP) and two condylar points (CP) to fully define the dominant movement of the jaw [20], the trajectory of the IP is sufficient for the use of trajectory generation as the subject's head is fixed in the system and the jaw movement has no rotation. We cannot simply use the ROM of the IP to define the ROM of each attachment in the system; this part is remained for further work. Rotation angle of this system should be larger than human jaw's opening angle, 27°. [4]

B. Electronic System

The electronic system includes all the sensors and the electronic circuit. The sensors should be able to measure desired parameters, for example the jaw angle and the torque applied on the jaw, in real time. In addition to this, they should be able to achieve required high sampling frequency, high precision and low noisy level. At least four kinds of sensors are necessary in this system, where EMG sensors are used to detect EMG signals, vibration sensors are used for the TMJ noise examination, load cells are used to detect torque signals, and hall sensors are used to detect position signals.

C. Microcomputer

The microcomputer should be able to control the motors and the loud speaker; receiving signals, display the real-time assessment, generate clinical report, and store data.

D. Software-Based Control System

The software-based control system is stored in the microcomputer. For better understanding, this system is discussed individually instead of including in the microcomputer part. The control system is necessary for the purpose of realizing close-loop control and multi-functional requirements (Figure 7).

assist-as-needed (AAN) function. Without the specific mechanical system, the approach for the compensation cannot be discussed right now; and additional sensors may be needed.

A torque signal generator is used to generate the torque signals when the jaw is outside the visual tunnel. The (3.1), (3.2), and (3.3) are designed formulas, where $\underline{p}_{3 \times 1}$ is a matrix of desired positions, $\underline{p}'_{3 \times 1}$ is a matrix of measured positions, l_{i1} is the width of the visual tunnel, and τ_{i1} is the torque signal.

$$\underline{p}_{3 \times 1} = \begin{bmatrix} \theta_{open/close} \\ \theta_{left/right} \\ x_{forward/backward} \end{bmatrix} \quad (3.1)$$

$$\underline{p}'_{3 \times 1} = \begin{bmatrix} \theta'_{open/close} \\ \theta'_{left/right} \\ x'_{forward/backward} \end{bmatrix} \quad (3.2)$$

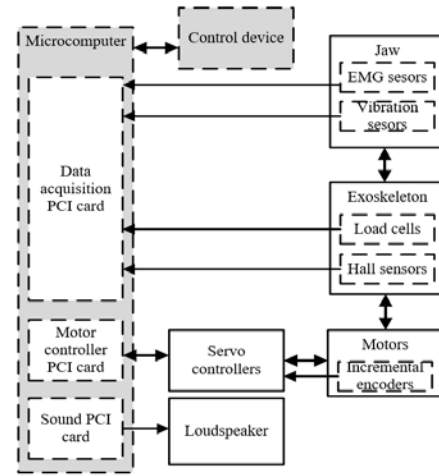


Figure 8. Initial hardware system design

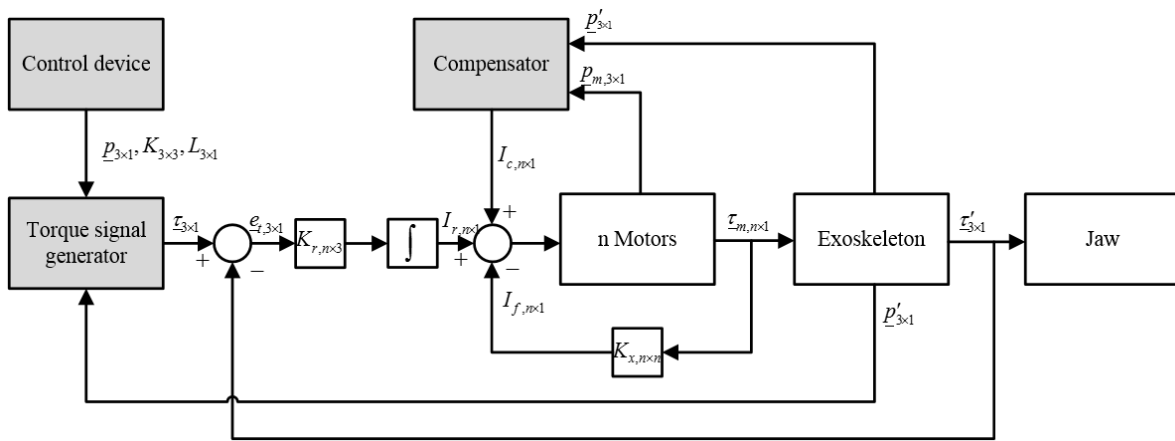


Figure 7. Software-based control system

Firstly, this system should compensate resistances, including gravity, normal friction, column friction, inertia, and backlash, generated by the mechanical system to achieve

$$\tau_{i1} \Big|_{i=1,2,3} = \begin{cases} 0 & \text{if } |p_{i1} - p'_{i1}| < l_{i1} \\ k_{i1}(p_{i1} - p'_{i1}) & \text{if } |p_{i1} - p'_{i1}| \geq l_{i1} \end{cases} \quad (3.3)$$

Full state feedback and reference tracking are used in this state-space model control.

E. Initial Hardware System Design

Figure 8 shows the initial hardware system design based on the previous discussion. During the CPM therapy, firstly, clinicians set the necessary parameters on the control device, which are used to derive the required torque signals. The signals pass through the PCI card, the servo controllers, the motors, and controls the exoskeleton to apply desired torques on the jaw. Meanwhile, the position signal, the torque signal, the EMG signal, and the vibration signal measured from the sensors are sent back to the microcomputer through the data acquisition card, and they are for clinical assessment and close-loop control. During relaxation therapy, the EMG sensors can detect if the patient is unconsciously and/or stretches his facial muscles. If it's true, a sound signal will send back to his ears. Then patient can manage and relax himself.

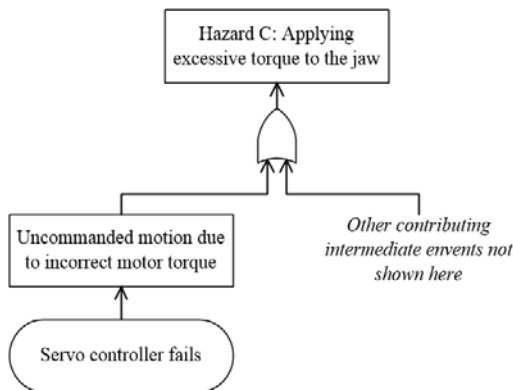


Figure 9. The initial fault tree of hazard C

Although most previous robot designs have several safety components, researchers did not systematically analyse their safety strategy. Here, a safety analysis method in the design is presented.

The Figure 2 illustrates the detailed steps. Firstly, three preliminary hazards are identified:

- Hazard A: Moving the jaw outside its safe ROM
- Hazard B: Moving the jaw at an excessive velocity
- Hazard C: Applying excessive torque to the jaw

Take hazard C as an example. A single failure of the servo controller is, potentially, capable of producing an un-commanded torque to the jaw. According to this, a fault tree could be drawn like the figure 9. The project safety criteria

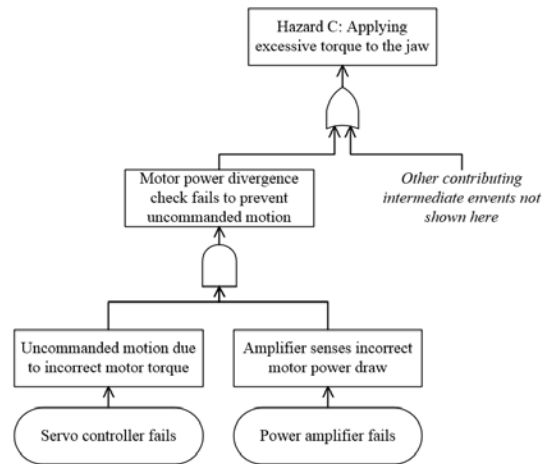


Figure 11. The redesigned fault tree of hazard C

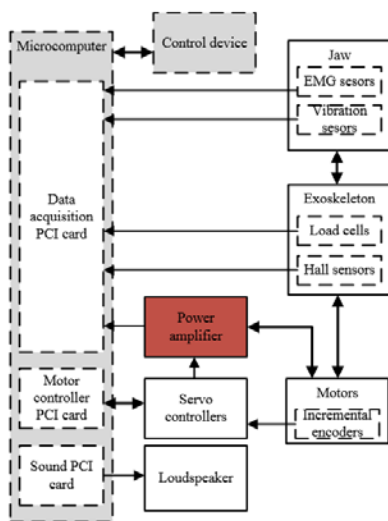


Figure 10. The redesigned system

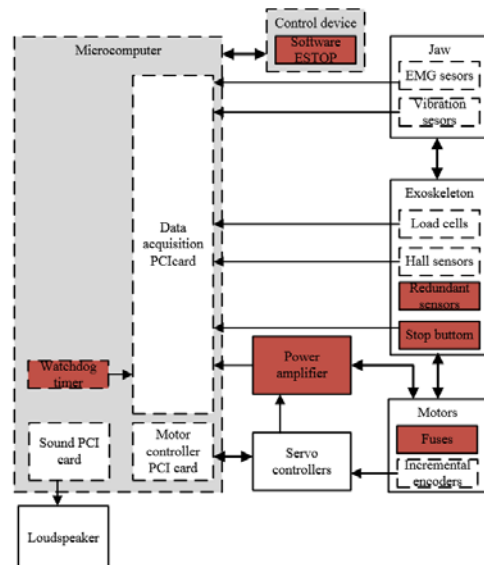


Figure 12. Final hardware system design

F. Safety

For rehabilitation robotics, safety should be the highest priority as the patients are more vulnerable than others.

in my design specify that no single failure can cause a hazard and the system must be fail-safe. As a result, this kind of fault tree cannot pass the evaluation, because the single failure can cause the hazard. Then the system is redesigned by adding a

TABLE I. ASSESSMENT FACTORS FOR REHABILITATION ROBOTS

Factors	Important to whom	Evaluation method	Summary of key leverage
New treatment options	Clinical researchers, patients	Questionnaire, cost-benefit analysis (CBA)	<ul style="list-style-type: none"> ● Achieve 3-DOF movements ● Able to simulate human's mastication movement ● Incorporation of biofeedback treatment ● Speed up clinical research through greater consistency and data gathering
Quality	Clinicians, patients	Questionnaire	<ul style="list-style-type: none"> ● Improve the quality of rehabilitation technique
Time and cost	Clinicians, hospitals, patients	Questionnaire, cost-benefit analysis (CBA)	<ul style="list-style-type: none"> ● Speed up rehabilitation time ● Reduce costs for both patients and hospitals ●
Less invasiveness	Clinicians, patients	Simulation, questionnaire	<ul style="list-style-type: none"> ● Provide important information and feedback required to reduce the invasiveness ● Reduce operation errors
Safety	Clinicians, patients	Simulation	<ul style="list-style-type: none"> ● Fail-safe
Real-time feedback	Clinicians	Questionnaire	<ul style="list-style-type: none"> ● Provide accurate information about the patient
Enhanced documentation	Clinicians, clinical researchers	Questionnaire	<ul style="list-style-type: none"> ● Store clinical information ● Improve clinical practice and shorten research trials

separate power amplifier (Figure 10). By comparing the motor current draw with the requested output of the servo controller, it can determine if either component is at fault. Now the safety criteria were satisfied by this updated fault tree (Figure 11). Without enough historical and experimental data, the quantitative analysis cannot be done in this design. Eventually, this final system design is achieved with additional redundant sensors, watchdog timer and fuses (Figure 12).

IV. CLINICAL APPLICATIONS OF THE ROBOTIC EXOSKELETON

A. Factors driving acceptance

Just as with manufacturing robots, the robotic exoskeleton in the rehabilitation of TMD must reveal its real advantages if it is to be accepted and widely popularized. Taylor, Russell H., and Leo Joskowicz listed eight assessment factors for medical robots: new treatment options, quality, time and cost, less invasiveness, safety, real-time feedback, and enhanced documentation. [21] Table I lists these factors and related information.

B. Roboethics

Veruggio defined roboethics as 'Roboethics is an applied ethics whose objective is to develop scientific/ cultural /technical tools that can be shared by different social groups and beliefs. These tools aim to promote and encourage the development of Robotics for the advancement of human society and individuals and to help preventing its misuse against humankind'. [22] According to this, the subject of roboethics is not robots but the robots' designer, manufactures, and end users. He and Operto provide several rule which these people should follow when designing, developing, applying a new technology from the social and ethical standpoints. A part of these rules related to the design of TMD rehabilitation robotics is discussed below.

- Human dignity: Traditional rehabilitation robotics used in hospital would cause hardship and dignity issue. However, when developing a wearable robot on head, the human dignity is a vital consideration through the whole development considering its relatively large volume. Even for a hearing-aid,

people are making their every effort to make it as smaller as possible, or to make it as a decoration in order to reduce a feeling of shame when wearing it. For this relatively big exoskeleton worn on head, designer and manufacturers still have a long way to go.

- Benefit and harm: As mentioned in the last part, providing new treatment options and high rehabilitation quality can improve the benefits of the robot. Although robotic devices could cause more serious accidents, considering their large power and rigid mechanical part, than the traditional devices, the risk of using a robotic device is actually lower than a traditional one if the robot has passed strict project safety criteria.
- Nondiscrimination and nonstigmatization: Rehabilitation robotics are geared to the need of patients and the disabled who are relatively more sensitive for discrimination and stigmatization, so the designer should pay a lot more attention on the nondiscrimination and nonstigmatization rules. Especially, they should notice the influence of their description for the robot and the words shown on the user interface. For instance, when naming a robot, 'mouth opening training robot' shows less discrimination than 'TMD robot'.

APPENDIX A
Robotic Evaluation: Patient Feedback

Primary therapist to fill out with patient:

Check one:

- First experience
 Week of discharge

1. Did you like this treatment?	Yes _____	No _____
2. Do you feel it was helpful?	Yes _____	No _____
3. Was this boring?	Yes _____	No _____
4. Did you feel safe?	Yes _____	No _____
5. Was it confusing to use?	Yes _____	No _____

Additional comments which would be helpful:

Patient name: _____
 R.I. # _____
 Age: _____
 Sex: _____
 Date: _____

APPENDIX B:
ROBOTICS STUDY FOLLOW-UP QUESTIONNAIRE

- How long did it take to set up your patients?
- What took the longest in setting them up?
- Was this time satisfactory to you?
- Was setting up your patients complicated? If so, explain.
- Were the markers on the floor helpful in set up? If not, explain.
- Did the robot arm (not the computer) malfunction at any time? Please describe incidents.
- Did you feel at any time that your patient was at risk of being hit by the robot arm? If so, what could be done to prevent this?
- Would you feel comfortable leaving your patient alone to work? If not, what type of supervision would be needed?
- Did you feel hesitant to use this system initially due to a lack of computer or robotic knowledge/experience? If yes, do you still feel the same since using it?
- Did you ever use the data collected? Please explain your answer in detail.
- Was the data confusing? If so, explain.
- Would any other data have been more useful? Explain.
- How often did you generate a printed copy of this data?
- Was it easy to generate a report from the printer?
- Overall, would you say the patients' responses to the robot were positive or negative?
- Were the directions on the computer screen easy to follow? If not, explain.
- What would you change on the screen to make it easier to follow?
- Did the computer program work consistently upon your command? If not, explain problem.
- Please list memorable patient responses both pro and con.
- Overall, was your response to this positive or negative? Please list your pros and cons.
- Were the available patterns adequate to meet your needs? If not, explain.
- Were you able to obtain therapeutic movements from the established patterns?
- Would you have preferred to program your own patterns?
- Do you feel this was a valuable treatment modality for motor relearning? Why or why not is it valuable?
- What do you see as its limitations at this point?
- What type of patients would benefit from this modality in its current stage?
- How would you like to see it further developed?
- If you were an OT director would you want to order one of these systems for your clinic? Why or why not?

Figure 12. Questionnaires for the patient and the clinician [23]

- Informed consent:** For both research purpose and treatment purpose, researchers or clinicians are obligated to obtain informed consent from their subjects or patients. Researchers should fully inform their subjects of their research purpose, overall process, potential risk, and so on. Clinicians should inform their patients of potential risk, expected effect, and so on.
- Privacy and confidentiality:** Subjects and patients' personal information and clinical data should be kept in high degree of confidentiality to protect their privacy.

C. Evaluation Methods

There are a number of ways to evaluate the rehabilitation robot. Considering role, accuracy, and convince, all the factors related to the acceptance and ethics can be evaluated by a

combination of three methods, namely questionnaire, simulation, and the CBA.

- Questionnaire:** In clinical test, patients and clinicians' opinions are valuable feedbacks to evaluate these factors. The questionnaire can be used to evaluate whether the patient feels safe, the clinicians feels convince, and so on. The figure 12 shows two questionnaires designed to assess the patient acceptance and therapist acceptance. [23] Similar questionnaires can be used for the rehabilitation robot.
- Simulation:** The robot cannot be worn on the human and run in operation before being evaluated by human-oriented tests. [4] By testing on the jaw simulator, researcher can evaluate its safety and performance.

- CBA: The cost-benefit analysis can be used at different stages of the design. For instance, it can be used to compare advantages and disadvantages between two design schemes.

V. CONCLUSION

A safety-critical robotic exoskeleton for rehabilitation of TMD has been designed, which can provide the CPM therapy, the biofeedback and relaxation therapy, the ROM examination, and the TMJ noise examination. And with a combination of the three evaluation methods mentioned above, all the factors of this robot related to the acceptance and ethics can be assessed. However, this project just defined the scope of the research, and it still has a long way to go.

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Exoskeleton for Rehabilitation of Temporomandibular Disorder – System Design Requirements and Considerations

James Hope

Abstract – Temporomandibular disorder (TMD) can be caused by a range of medical conditions related to the tissues surrounding the temporomandibular joint (TMJ) as well as neuromuscular conditions such as cerebrovascular accidents.

A common treatment/rehabilitation method is physical therapy and/or exercise therapy; these are favoured initial approaches as they are non-invasive and reversible. In many other parts of the body, particularly the upper and lower limbs, assistive and rehabilitative robotics have been introduced to aid the physical therapist and clinicians. Comparatively, the application of robotics to rehabilitation of TMJ is relatively undeveloped. This is in some part due to the lack of robotic devices designed to undertake the required tasks.

The main design objectives of an exoskeleton robot for rehabilitation of TMDs are: assisting physical therapists in their duties; cost savings and improvement in treatment efficiency and accessibility; improving patient outcome; improving consistency in patient outcome measurement. These design objectives are closely aligned with the potential benefits of rehabilitative robotics.

A review of previous research into the kinematics and dynamics of the TMJ, development of masticatory robots, and robots for rehabilitation of TMD is performed. The findings from this review are combined with the design objectives and benefits of robotics in order to generate a list of fifteen system design requirements. These are divided into six sub-groups: Kinematics, Patient Data / Sensor Feedback, Rehabilitative functionality, Interface, Accessibility, Safety.

I. INTRODUCTION

The term temporomandibular disorder (TMD) refers to a group of medical conditions associated with the temporomandibular joint (TMJ), facial muscles used for mastication, or both [4]. The underlying causes for TMD varies widely and is not always clearly understood, however they can be broadly grouped into being either musculoskeletal or neuromuscular in nature [2, 5].

TMD patients may experience one or more of the following symptoms: pain in the TMJ, facial muscles, neck, shoulders and around the ear; limited range of motion within the TMJ; clicking or popping noises during motion of the TMJ; locking of the TMJ; headaches, toothaches and earaches; tinnitus; among others [4, 6]. The limits which these symptoms can place on the performance of necessary daily activities, such as eating and speaking, provides the correlation between

successful treatment and an improvement in the quality of life [4].

The Research Diagnostic Criteria for Temporomandibular Disorders (RDC/TMD), originally published in 1992 and then republished in 2010, provides a protocol to aid classification of TMDs into three groups, within which sub-groups also exist; “Group I, myofascial disorders; Group II, disk displacement with or without reduction; Group III, arthralgia, arthrosis, and arthritis” [7]. The recommended method of treatment varies depending on the nature of the disorder and the patient characteristics. It is generally agreed on by experts that the initial treatment for TMD should always be conservative, non-invasive, and reversible [8-10].

Non-reversible, invasive treatments are surgical in nature and so present risks of permanent scarring and nerve damage. They include arthrocentesis, arthroscopy, discectomy, and replacement of the joint with an implantable prosthesis [6, 7, 10].

Conservative, non-invasive and reversible treatments include education, self-management or self-care techniques, medication, splints, exercise therapies; where a patient rehabilitation regime may contain several of these treatment methods [6, 7, 10]. It is reported that conservative treatments can successfully treat between 85% and 90% of TMD [9].

Manual physical therapy and exercise is conducted through the instruction and guidance of physical therapists. Physical therapy is generally performed on the patient by the physical therapist, and exercise by the patient at home. Even when non-reversible treatments are employed, physical therapy may have a post-surgery role to aid recovery and prevent reoccurrence [11, 12]. The evidence supporting physical therapy for treatment of TMDs is positive in outcome but not yet considered significant or comprehensive due to the relatively low number of clinical studies conducted so far, and inconsistencies between studies in the outcomes measured [13-15].

On the other hand, physical therapy is a commonly applied treatment for rehabilitation of the upper and lower limbs for motor function impairments caused by certain medical conditions. This includes neuromuscular conditions such as cerebrovascular accidents (CVAs) commonly known as stroke, and musculoskeletal conditions such as occupational injuries. Particularly in the case of CVAs a good body of research and clinical

trials has been performed in evaluating the efficacy of physical therapy with positive results [16, 17]. CVAs are one of the medical causes of TMD [5].

The use of robotics in physical rehabilitation for CVAs has been shown to provide comparable results in patient outcome to that of conventional therapy for a given duration and intensity [18]. Furthermore, again for CVAs, when robotic is used as an adjunction to conventional therapy the patient outcome significantly improves compared to just conventional therapy [19]. Both of these phenomena held drive research in the area of rehabilitative robotics.

Two surveys conducted on physical therapists discussing issues of rehabilitative robotics in clinical settings provided generally positive responses, though with some caveats. One major caveat is that to be accepted into clinical settings robotic assisted therapy should not only replicate conventional techniques but provide additional features or benefits. Another equally if not more important caveat is patient and user safety and the devices usability [16, 20]. These concerns can be addressed through design consideration.

The objectives of an assistive/rehabilitative exoskeleton can be summarised as follows:

- Assisting physical therapists in their duties
- Cost savings and improvement in treatment efficiency and accessibility
- Improving patient outcome
- Improving consistency in patient outcome measurement

The design process must address the above objectives while ensuring patient and user safety through risk management, accessibility through universal design principles, and user/patient acceptability through design-for-user principles.

II. BIOLOGICAL SYSTEM

The TMJ produce motion of the mandible bone which sits inferiorly, relative to the temporalis bone, which sits superiorly. Mastication is a common and complex articulation of the TMJ and so is used here as an example to describe the musculoskeletal interactions. Mastication involves both jaw opening, or mandibular depression, jaw closing, or mandibular elevation, as well as, protrusion, lateral and medial deviations of the mandible. Excluding the weaker muscles involved in opening of the mouth there are three muscle groups involved in mastication; the temporalis muscle, which can be further subdivided into anterior and posterior elements; the masseter

muscle which consists of the superficial and deep parts; and the pterygoid muscle group, which consists of upper & lower lateral pterygoids and superficial & deep medial pterygoids. The temporalis, masseter and medial pterygoids primarily contribute to closing the jaw; the upper and lower lateral pterygoids are major contributors to lateral and medial deviations of the jaw [2]. For simplicity these sub elements of the muscle groups are not included in Figure 1 and Figure 2, which show the bones' and muscle groups' location around the TMJ.

The TMJ contains a soft tissue component called the intraarticular disc, which is located between two articular surfaces consisting of fibrocartilage. One surface is on the condyle of the

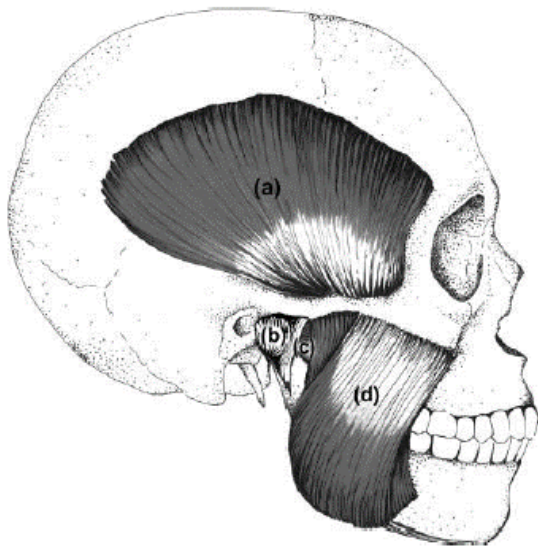


Figure 1. "Superficial view of temporomandibular joint (TMJ) anatomy. (a) temporalis muscle, (b) temporomandibular ligament, (c) lateral pterygoid muscle, and (d) masseter muscle." Figure and description taken

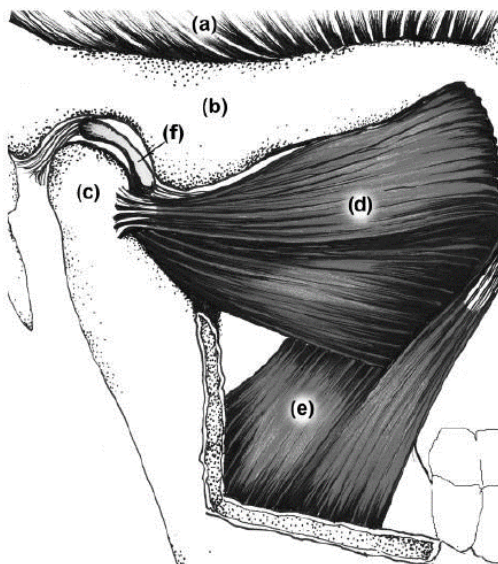


Figure 2 "Deep view of temporomandibular joint (TMJ) anatomy. (a) temporalis muscle, (b) temporalis bone, (c) mandibular condyle, (d) lateral pterygoid muscle, (e) medial pterygoid muscle, and (f) intraarticular disk". Figure and description taken directly from [2].

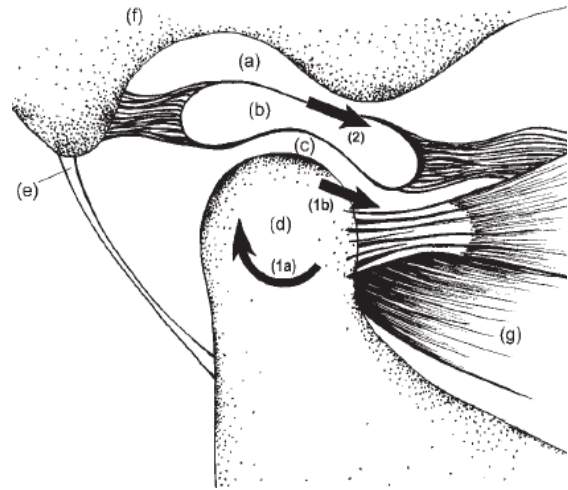


Figure 3. "Temporomandibular joint (TMJ) arthrokinematics during mouth opening. (a) discotemporal space, (b) intraarticular disk, (c) discomandibular space, (d) mandibular condyle, (e) posterior joint capsule, (f) temporalis bone, (g) upper and lower heads of the lateral pterygoid muscle". Figure and description taken directly from [2].

mandibular, and the other extends from the temporomandibular fossa along to the articular tubercle [2, 21]. The mandibular condyle can vary in shape between patients, and even vary within patients between the two joints on either side of the mandibular. "Condyle shapes have been previously described as convex, flat, angular, and rounded" [2], and are subject to degenerative changes over time, both locally and extensively. The latter case can involve total loss of cartilage on the mandibular condyle.

The intraarticular disc can also undergo degenerative changes, and in addition to this can be displaced within the joint, relative to its normal position, anteriorly, posteriorly, medially, or laterally. The intraarticular disc is directly attached to the temporalis bone on one side, and to the pterygoideus muscle structures on the opposing side such that it moves with the condyle of the mandible under the temporalis during articulation, as indicated by arrows 1b and 2 in Fig. 3 [2].

III. KINEMATICS

The TMJ can be simplified to a combination of hinge (arrow 1a in Figure 3) and sliding joints (arrow 1b in Figure 3.), however authors also note the presences of spinning and compression as well [2]. Unlike other joints, where the axis of rotation is fixed, the two articulating surfaces which guide the TMJ allow more complex combinations of movements. Furthermore the joint isn't restricted to follow paths on predefined pathways, but can achieve positions and follow

trajectories anywhere within a multidimensional space envelope consisting of positions in the linear axes X, Y, Z plus rotary axes U, V, W. This is referred to as the Posselt envelope. The boundaries of which are defined by the maximum posterior jaw open position, maximum anterior jaw closed position, and maximum upper glide of the mandible which denotes protrusion of the jaw [21].

Values for these boundaries are provided by Shaffer *et al* (2014) [2] for patient groups broken down by age range and gender.

IV. DYNAMICS

Peck (2015) [22] investigated the biomechanics of occlusion. Occlusion is the interaction of teeth when the jaw is closed or in a near closed position, and plays a prominent part in the complex shape of the upper surface of the Posselt envelope. He notes that while the magnitude of bite forces vary widely between subjects, due to physiological reasons, in all normal cases they predominantly occur in the vertical (Y) and parallel (X) direction relative to the long axis of the teeth, shown in Figure 4, and to a lesser but not insignificant extent shear forces occur laterally (Z) and anteriorly/posteriorly (X). In addition to this the largest force component is present across the molars. The significance of modelling forces within the mouth in this way becomes evident when maxillary and/or mandibular teeth are missing; these structural changes in the jaw of the patient can change the Posselt envelope, discussed earlier, lead to changes in the jaw dynamics, and changes in the functions of muscle groups.

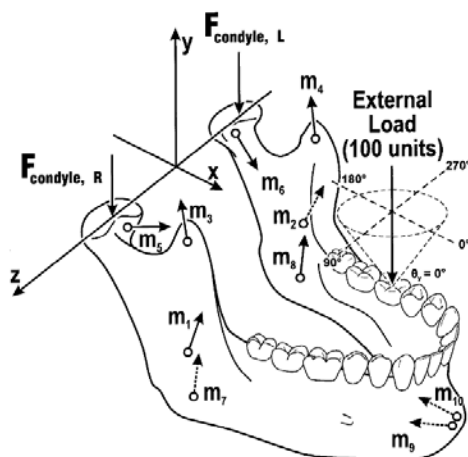


Figure 4. Axis notation and force vectors on the mandible. $F_{condyle}$ notates joint forces, m_x notates muscle force vectors. The symmetry of the left and right sides of the musculoskeletal architecture in the mandible is evident; $m_{1,2}$ denote masseters; $m_{3,4}$ anterior temporalis; $m_{5,6}$ lateral pterygoid; $m_{7,8}$ medial pterygoid. Taken from [3]

Wang *et al* (2012) [23] review biomechanics of the TMJ, in particular loading of the intraarticular disc. They explore several models derived from Finite Element Modelling (FEM) for static stress-strain analysis under loading, and the more realistic approach of combining of FEM static analysis with multi-body dynamic analysis (MDA). They provide an analysis and summary of the mechanical properties typically used for the associated bone, ligament, cartilage and articular disc components, along with recommendations on the material behaviour (e.g. linear elastic, non-linear elastic, viscoelastic, Hill-type).

Iwasaki *et al* (2003) [3] employed commonly used numerical models and compared these to experimental data. The experimental approach used electromyography measurements, with either surface or indwelling electrodes, in combination with jaw tracking. Their investigation focused on two points: 1) the variation in bite force across a range of TMJ offset positions in the X axis (protrusion) where the two extremes are molar biting and incisor biting; 2) the coordination and degree of recruitment of muscle groups during mastication are with the intention of minimising the forces in the joint and minimising muscle effort required for the task. An interesting finding is the non-linearity of the muscle output for “changes in magnitude and direction of moments applied to the teeth”.

V. ROBOTIC EXOSKELETON DEVICES

The body of literature on the development and application of jaw exoskeletons and their clinical results is not as extensive as other fields, for example, exoskeletons used in upper and lower limbs.

Early work in this field was undertaken by Takanobu and Takanishi, who began development of masticatory robots in 1986. Their first human masticatory robot, the WJ-3 (Waseda Jaw), presented in a 1993 paper [24], was designed as an investigative tool into the biomechanics of mastication. It contains thorough analysis of jaw kinematics and the sensors required to properly evaluate jaw motion and joint force.

In a later study by Takanobu, Takanishi *et al.* (1997) [25] the authors address a large drawback of the WJ-3 robot, which is that the electromagnetic motors are not representative of the true viscoelastic response of muscles. They present a mathematical model for the variable viscoelasticity found in human muscle, and then modify their actuators to encompass similar

properties. These modified artificial muscle actuators (AMA) are built into the WJ-3RII (Revision II) robot.

Takanobu, Takanishi and his colleagues continued their work in this field, publishing a paper in 1999 which presented the first robotic assisted jaw robot for rehabilitation [26], named the WY-2 (Waseda-Yamanashi-2). While this robot encompassed all of the kinematic and dynamic design features which were developed using the WJ series of robots, this new design as designed to interact with patients. Its mechanical structure embodied a combination of sliding and hinge joints to mimic the TMJ. The resultant 3 dimensional work space of the robot was comparable to that of a humans Posselt envelope. Integrated force sensors were able to measure bite force in the X, Y and Z axes, load cells to measure opening force, and strain gauge sensors to measure the anterior/posterior forces and lateral force.

A drawback of the WY-2 and a later version, the WY-3, robot designs is that it only encompassed 3 degrees of freedom (DoF), vs the human's 6 DoF. Takanobu, Takanishi and his colleagues amended this problem with a 6 DoF robot made using a parallel kinematic actuator configuration, the WY-5. This was presented in a 2000 paper [27] along with preliminary clinical

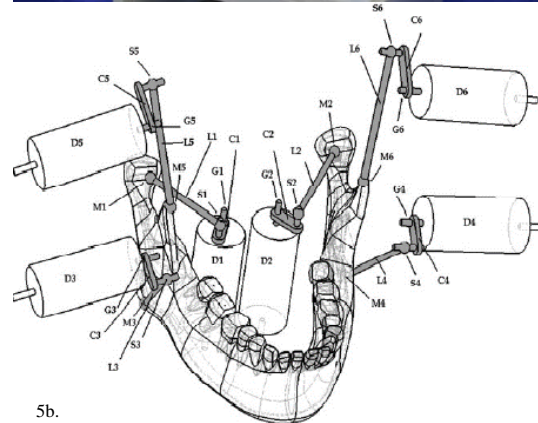
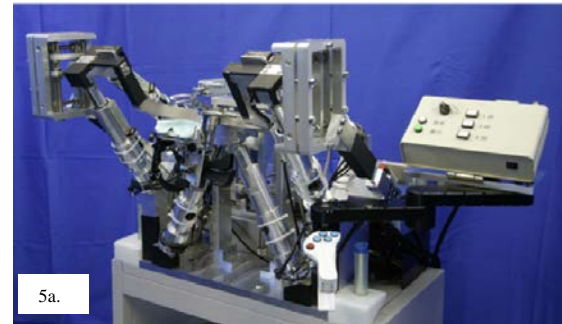


Figure 5a. The WY-5IV 6-DoF jaw exoskeleton, with parallel kinematics, 6-DoF sensor and software compliance control, by Okina and colleagues. Taken from [1].

Figure 5b: Schematic of the robotic jaw with parallel kinematics designed to mimic human jaw musculoskeletal structure, later built by Xu and colleagues. Taken from [1]

results; which was further expanded in a 2003 paper [28]. The 6-DoF WY-5 uses standard linear actuators, not the variable viscoelastic AMA actuators developed for the WJ-3. Viscoelasticity, or rather compliance, is instead introduced into the system via the software and control method. This approach is evidently required as the parallel actuator configuration is no longer directly representative of the muscles within the jaw. A drawback of this approach is that it relies on sensor information to feed into the control loop. The force sensor feedback in this design was restricted to the X,Y and Z axes, i.e. the user appears to be unable to programmably set the stiffness of rotational axes.

Okino *et al* present an upgraded version of this 6-DoF robot, the WY-5IV, which incorporates a 6-DoF force sensor, in a 2004 paper [29]. This improved force sensor integration allows control of the compliance (spring stiffness and damping) over the linear and rotational axes. This was then use to apply what the authors refer to as intermaxillary therapy on a patient with a fixed open-jaw, i.e. unable to completely close their jaw. The clinician is able to programmably set the compliance in each axis and so the degree of guiding provided to the patient during jaw exercise.

Xu *et al* reviewed jaw biomechanical models and masticatory robotics in a 2008 paper [1], including their work, which began in 2002, in development of a robotic jaw used to investigate and analyse food properties. In a human the mandible can be thought of as the end effector, and the three muscle groups outlined earlier as the actuators; thus we have a parallel kinematic system. This parallel actuator configuration was replicated in Xu *et al*'s design, shown in Figure 5. The researchers also designed their system to model the actual human jaw by determining the placement and direction of actuators based on the muscle vectors shown in Figure 4.

Wang *et al* [5, 30] build on work presented so far with the intention of improving the WY-5 series of 6-DoF exoskeletons. In particular they address the inaccessibility to patients posed by the WY-5 series due to its bulky size, portability and perhaps cost of the device. These factors all restrict its application in neurological TMD which benefit from increased intensity, duration and number of repetitions as covered earlier. The authors design and build a lightweight wearable exoskeleton though with reduced features and functionality vs. the WY-5IV. They use a four-bar linkage between the actuator and jaw coupling in order to generate target trajectories. The device is able to be customised to suit different geometries between users, and to change the trajectory. However, during use the moving jaw coupler follows this pre-defined path. The nature of a four bar linkage only allows it to generate motion within a 2D plane; furthermore the 1 DoF joints used with the exoskeleton and symmetrical lay-out between the two four-bar linkages (one on either side of the jaw) restrict motion of the exoskeleton to this 2D plane (XY).

As outlined in the Introduction of this report, the clinical efficacy of physical therapy and jaw exercise is regarded as positive in outcome but requiring more trials to provide statistical and clinical significance to the results. No clinical trials have been found which used any of the robotic devices presented here.

Limited clinical studies exist on passive exercise devices. The Therabite system which produces jaw anatomically correct jaw motion but is limited to a 2D plane (XY), results on patient outcome were positive [31, 32]. Another simpler device with 1-DoF also showed positive results [33]. Both require higher number of trials, and more comprehensive clinical trials in order to be statistically and clinically significant.

None of the reviewed devices can conclusively address all of the objectives outlined earlier in the *Introduction*.

VI. SYSTEM REQUIREMENTS

The potential benefits which robotics have to offer to the treatment of TMD, and more generally to the field of rehabilitative medicine, can be summarised as follows:

1. To free up resources and so make cost savings and improvements in treatment efficiency. This is done by robotic devices' ability to reduce the number of clinicians/physical therapists and/or the amount of direct assistance from clinicians/physical therapists required by the patient during treatment sessions [16, 20]
2. Robotics allow functions to be carried repetitively without variation due to either fatigue in the therapist, or natural human variation which occurs when performing repeated tasks. For neurological TMDs increasing the intensity, duration and number of repetitions all positively affect the outcome [18]
3. Integrated mechanics and sensors allows for precise control and measurement of parameters during therapy, including but not limited to: voluntary torque, applied resistance, trajectory control, velocity consistency, range of motion, end position accuracy. This information can be collected and provided to the therapist [34]
4. The programmable nature of robotics allows the therapist to change parameters easily and precisely. This aids implementation of progressive therapies, which involves gradually increasing one or more parameters, such as resistance or range of motion, as the patient's condition improves. It also allows customisation of the robotic assisted therapy to the condition being treated [14, 35].
5. Various modern forms of augmented feedback try to motivate patients and help eliminate onset of boredom during repetitive tasks; for example a virtual reality environment with games-based tasks which respond to movement of the patient. Where proprioceptive initiation of exercise tasks is critical to success in treating neuromuscular conditions [34], and the frequency and task specificity of exercise benefits treatment of musculoskeletal conditions [5].

Many of these are complimentary to the objectives outlined earlier, repeated below;

therefore we can be confident that robotics are a good approach to this problem:

- Assisting physical therapists in their duties
- Cost savings and improvement in treatment efficiency and accessibility
- Improving patient outcome
- Improving consistency in patient outcome measurement

While ensuring user safety, accessibility and user/patient acceptance.

By comparing the benefits of robotics to the design objectives we can derive a list of requirements for the exoskeleton. These are grouped into six sub-systems below; the sub-systems will all involve hardware, electrical and software elements. Implementation of the requirements into a design concept must be based on the biomechanics of the jaw covered in earlier sections of this report.

Kinematics:

1. 6 DoF movement via either a serial or parallel kinematic actuator configuration is required to accurately mimic motion of the jaw in 3D space, as defined by the Posselt envelope.
2. The system range of motion should be adjustable to account for each patient's Posselt envelope. Ideally it should use information from the patient to define this, due to the complex surface profiles of the Posselt envelope generated by interaction of teeth. This must also be able to change during therapy to account for incremental improvements.
3. The actuators should be compliant, modelled as a spring and damper in parallel, and be programmable so that the compliance in each of the 6 axes can be controlled and adjusted.

Patient Data / Sensor Feedback:

4. 6-DoF force feedback via sensor hardware should be integrated in order to provide a) feedback on the human-robot interaction and b) information about the forces in the TMJ. The range and accuracy of each sensor must be considered.
5. Placement of sensors must be considered; for example a) within the robot joints and actuators; b) At the patient/user interface; c) on the patient skin, or sub-skin surface (within muscle mass); d) within the mouth (bite forces and distribution between teeth).
6. Mathematical/biomechanical model used to link sensor data to the measurements provided to users and patients. The method to input data into this model, and how this data is gathered

for each patient (e.g. through radiography imaging, scanned CAD of patient etc.).

7. Jaw trajectory following via a camera in 2 or more planes, or other multi DoF sensor could be considered to monitor the trajectory of the jaw during therapy. The accuracy must be defined, ethics considered.
8. Sensors which can measure the degree of patient effort such as EMG; or software systems which can infer this factor such as through results in game-based interactive environments.

Rehabilitative functionality:

9. The system should be capable of active and passive assistive movement of the mandible; and a programmable variable degree of assistance.
10. The system must be able to follow user defined 6 DoF trajectories in 3D space, through generation of sufficient velocities, acceleration and jerk typical of healthy and TMD affected TMJs. Actuator bandwidth falls into this category.
11. Suitable for repetitive use at a given frequency for a given amount of time. The maximum on time / off time and corresponding duty cycle should be defined based on clinically approved exercise therapy specifications.

Interface:

12. Software interface / GUI should be understandable by physical therapists. Minimum input and output/feedback requirements are the voluntary force from patient, applied resistance from robot, target trajectory control, trajectory error, velocity consistency, range of motion/boundaries.

Accessibility:

13. An ideal system is lightweight enough to be both wearable and portable. Failing that a portable system still allows flexibility for the user and patient. Failing this a transportable system with minimal set-up requirements. Must be consideration to the system complexity and the size, weight and number of auxiliary components supporting the system.
14. System cost; this mainly falls into accessibility category. If the system is prohibitively high in cost then it can restrict the rate and degree of adoption into rehabilitation / treatment centres and/or the number of patients which can use the device.

Safety:

15. User and patient safety is paramount. The mechanical, electrical, software, user-interface/usability sub-systems should all contain safety features which limit the position, velocity, acceleration, and applied torque. Both patient and user (clinician) should have access to stop switches. Compliance with the relevant international standards on exoskeleton medical devices, including implementation of additional risk management procedures, are a critical step in addressing and ensuring safety.

The next steps in the design process are as follows:

- Define the technologies which can achieve these requirements.
- Define the sub-systems required, using the selected technologies.
- Define quantitative specifications for each sub-system.
- Verify specifications and validate the system design.
- Clinical trials of the design

These steps are beyond the scope of this current report; however it is hoped that this comprehensive list of system requirements goes some way in aiding the design of an exoskeleton for rehabilitation of TMD.

VII. CONCLUSION

Research which has been performed to date which investigates the biomechanics of the jaw is valuable in helping to define rehabilitative and assistive exoskeleton robots for TMD. The results of clinical trials which measure the efficacy of physical therapy and exercise therapy for treatment of TMD are positive, however the quantity of research needs to be increased to improve clinical and statistical significance. Clinical trials which measure the efficacy of rehabilitative and assistive robots for TMD are almost non-existent, largely because it is still a relatively undeveloped field of engineering. It is expected that robotics has many potential benefits to offer in this field of medicine.

The potential benefits which robotics can offer treatment of TMD, outlined in this report, closely align with the design objectives which an exoskeleton device should achieve. It can be concluded then, that robotics are a good research approach to this problem. After reviewing the current research into jaw biomechanics and existing robot devices for treating TMD, a list of

preliminary requirements of a system were developed which address the design objectives.

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Design and Clinical Applications of a Robotic Exoskeleton for Rehabilitation of Temporomandibular Disorder

Xiaoxu Shi

Abstract—The aim of this research project is to develop a robotic exoskeleton for rehabilitation of TMD and discuss the clinical applications of the robotic exoskeleton relating to TMD. The conclusion of this project is that the robotic exoskeleton was developed based on the properties of the human mandible biological system and the general requirements for the rehabilitation training. The robotic system was divided into three subsystems to meet the functional and safety requirements. The clinical applications were discussed which include the devices, protocols, documentation and examination but to introduce the robotic exoskeleton into the clinical environment; many factors still need to be considered.

I. INTRODUCTION

Temporomandibular joint (TMJ) is a complex and highly mobile joint. As a crucial part of the human masticatory system, TMJ has big impacts on human food chewing, speaking and any motion relate to the mouth opening [1,2]. Jaw movement training with conventional mouth opening apparatuses is commonly used in the clinic environment for temporomandibular disorder (TMD) to help the patients who have problems opening and closing their mouths. Conventional mouth opening apparatuses are simply structures and the significant parameters are unknown during training. Consequently, the data to measure the improvement of the patient is limited in the mouth opening distance [3]. Moreover, the training with these simple mouth opening apparatuses is based on the doctor's technique through their experiences [4]. Based on the shortages of conventional mouth opening apparatuses and therapy, Robotic exoskeletons have been developed to improve the disadvantages of conventional apparatuses and increase the training efficiency.

TMD refers to a variety of conditions associated with TMJ and the masticatory muscles. Injury to the jaw, TMJ, or muscles of the head and neck can cause TMD [5]. The most common TMD are pain dysfunction syndrome, internal derangement, arthritis, and traumas [6]. One of the symptoms of TMD is that the patients are not able to open their mouths nor move their jaws. TMD commonly occurs between the ages of 20 and 40 years people and occurs more often in women than in men. According to the survey [7], there is 20-25% of the population exhibit symptoms of TMD. Also, it reports that 30 million Americans suffer from it, with approximately one million new patients diagnosed yearly [2]. As a reason, TMD is a problem that should be looked are more fully. The potential diagnosis of TMD appeared to be various, but can be categorized into neuromuscular dysfunction and musculoskeletal factors according to the formation of the disorders. Continuing and passive exercise, for limited jaw movement due to musculoskeletal reasons, has been proved to be effective to relieve the symptoms through improving the local metabolism in the joints and muscles [8].

The aim of this research project is to develop a robotic exoskeleton for rehabilitation of TMD and discuss clinical

applications of the robotic exoskeleton relating to TMD by using the mechatronics knowledge learned from courses and research articles.

II. LITERATURE REVIEW

A. The Biological System of Human Mandible

1) The Temporomandibular joint

The TMJ located between the temporal bone of the skull and the condyle of the mandible. The mandible moves about the skull under the control of the central neural system (CNS). As illustrate in Figure1, a soft tissue that called articular disc separates the condyle and the temporal bone to ensure the jaw moving along the mandibular fossa [9].

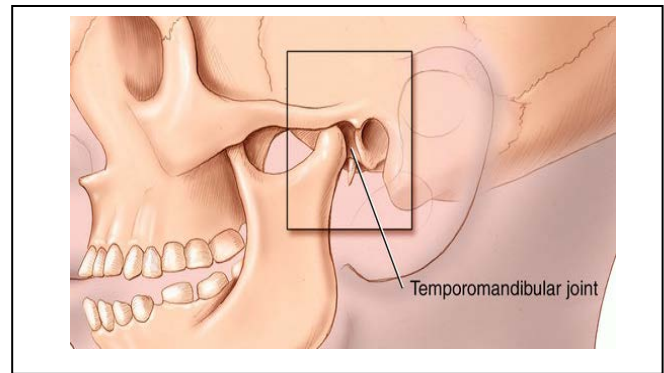


Figure 1. Temporomandibular joint

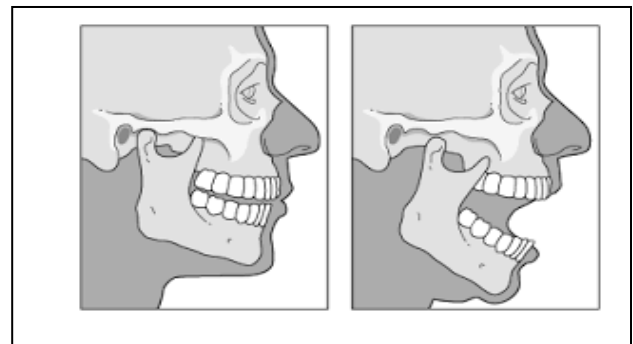


Figure 2. The movement of temporomandibular joint

The movement of TMJ is unique as shown in Figure 2, there is only a rotational movement in the first 20mm opening. For the wider open, the condyle and the disc have to move forward and down as a

translation. Moreover, it is noteworthy to point that the TMJ movement is not restricted along a fixed trajectory rather its movement occurs within an envelope of motion in three-dimensional space [10].

2) Mastication Muscles

The main muscles around TMJ include the masseter muscles, temporalis muscles, lateral pterygoid muscles, and medial pterygoid muscles as shown in Figure 3. [3]. The masseter muscles are attached between the cheek on the skull and the lower rear section of the lower jaw. The large temporalis muscles are attached from the side of the skull to the top of the lower jaw. The lateral pterygoid muscles are attached between the skull and the lower jaw in a horizontal fashion. The medial pterygoid muscles are attached on the inside of the skull and the lower jaw [9]. Consequently, the contraction between those muscles allows the lower jaw to move in the three-dimensional space.

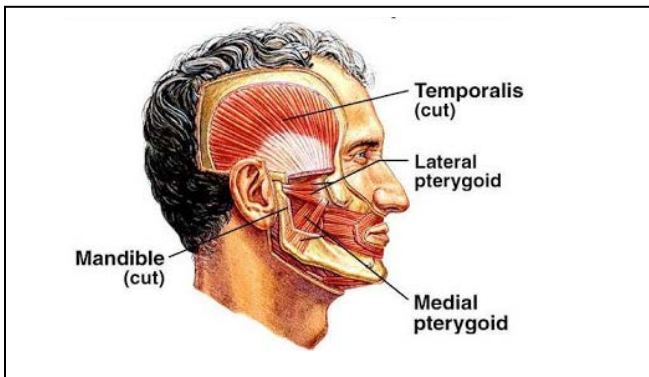


Figure 3. Main muscles around TM

3) Degree of Freedom (DOF) Characteristics

To develop the robotic exoskeleton, the understanding of mandible's DOF is significant. The ideal human mandible has 3-DOF, which are mouth open and close, forward and backward, and lateral motion. Precisely, it has 4-DOF as a parallel motion to the right and left. However, this motion is very small so it can be ignored. The DOF characteristics are illustrated in Figure 4.

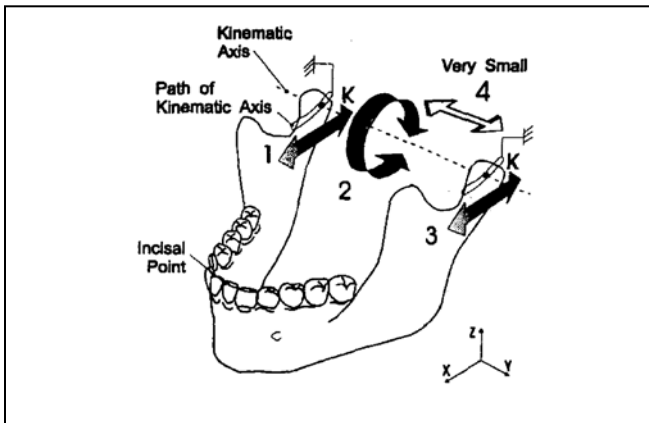


Figure 4. The Degree of Freedom characteristics of human mandible

B. Robotic devices for TMD rehabilitation

With the development of high technology, there is a variety of machines and devices available for reproducing human chewing behaviour and chewing force [11]. The research for masticatory robots has been developed since the early 1990s. These masticator robots could apply to the clinical environment such as dental training,

texture analysis, jaw simulation, and speech therapy. To compare with conventional apparatuses, this kind of robot can provide scientific measures for the clinical environment, and it has extensive development prospects.

The WY series robots are mouth training robots for the training of jaw disorder patients. The recent WY series robots are WY-5 and WY-6 which was developed by Waseda University of Japan [3]. These robots are parallel mechanism robot that have a 6-DOF mouth opening and closing movement that actuated by six linear motors via ball screws [12]. The robot can hold a patient's upper jaw and lower jaw by upper and lower mouth piece. The aim of the robots is primarily responsible for mouth opening and closing. Compared with conventional apparatuses that only able to perform the 1-DPF movement, this mechanism is more effective for JMD training. It is also proved that the robot can provide the clinical training for patients [13]. During the training, the quantitative data is the biting force acting on the patient via the mouth opening gauges. The doctor is required to operate a 2-DOF manipulator (open/close and forward/backward movements) or a 3-DOF manipulator (open/close, forward/backward and right/left movements). The photo of WY-5 robot is shown in Figure 5.

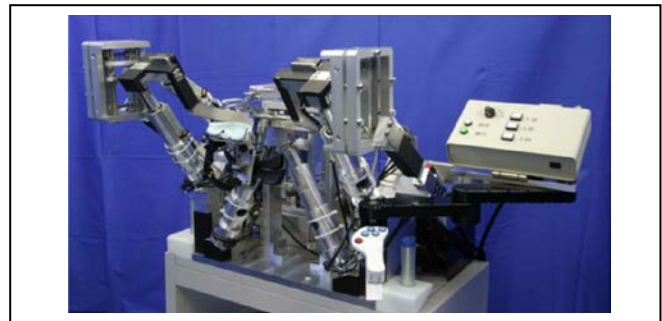


Figure 5. The photo of WY-5 Training Robot

The other typical robotic device for TMD rehabilitation is developed by Massey University [6]. The device is a wearable device composed of single-DOF linkage. The three-dimensional movement of the jaw is simplified as moving in the two-dimensional sagittal plane in this device [10]. The normal jaw motion is specified in term of incisor trajectory and condylar trajectory. A four-bar linkage is designed to meet the requirement, with adjustable links used for different patients. Compared with WY series robots, this device is more suit for intensive exercises in TMD rehabilitation. The system model of the device is shown in Figure 6.

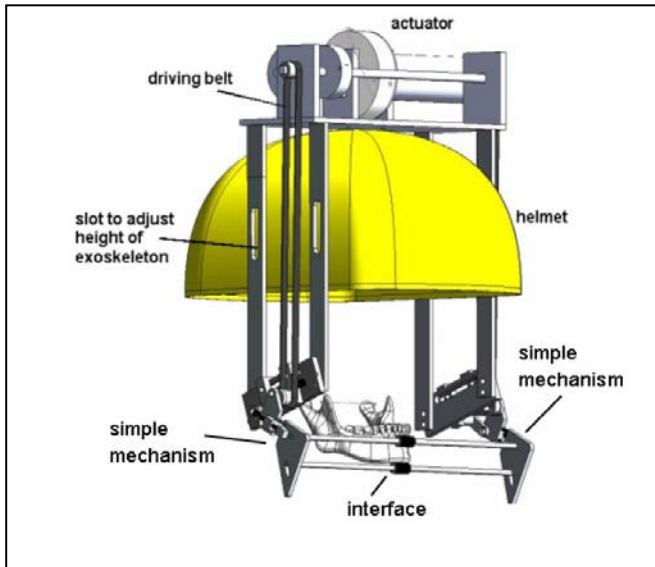


Figure 6. The wearable robotic device for TMD rehabilitation

There are many other mastication robots was developed for varies research purposes [11,14,15]. The WJ (Waseda Jaw) robot series was developed for patients to work with a WY series robot in dental training purpose. The WJ robot is used as a patient robot to understand patient's mastication movement and resistance forces during jaw opening and closing training. It could be also used for evaluating and treating TMJ dysfunction. The robotic jaw that developed by Massey University is aimed for analytically characterizing food texture. The device used to chew foods in a human way and, during the chewing the chewing the food parcels are collected and analyzed for food property evaluation.

III. CONCEPTUALIZATION AND SPECIFICATION

A. Qualitative and Quantitative specifications of the robotic exoskeleton

To establish a robotic exoskeleton for TMD rehabilitation, a mechatronic device is required to reproduce human chewing behavior. Many properties of the mandible that may be consisted into the exoskeleton that relate to the design specifications in both qualitatively and quantitatively. A basic mechanism of the exoskeleton should be designed by referencing the general requirements of the robotic exoskeleton. The qualitatively specifications of the robotic exoskeleton are shown in table I.

TABLE I. QUALITATIVE SPECIFICATIONS OF THE ROBOTIC EXOSKELETON

Item	Qualitative Criteria
Trajectory	Mouth open and close trajectories, forward and backward trajectories, and lateral trajectories
Range	Larger than maximum mandibular movement of human
Interaction	Attached inside of patients' upper jaw and lower jaw
Practice Time	Based on chewing cycle or could be set up by the operator
Operation Speed	Slow or smaller to the chewing speed
Operation Force	Conform to the average chewing force
Size and Weight	Optimum to small size and lightweight

The other essential parameter is the maximum mandibular movement that described by Posselt [9]. The maximum mandibular movement is a three-dimensional figure recorded by tracing the lower incisor teeth during guided jaw movements along the path. Figure 7 illustrates the Posselt envelope in the 3D plan. Because of the differences in genders and the mandible size, the measured movement could be a great variation. However, based on the evidence and research, the critical pathway can be approximated within a range. Typically, the maximal protrusion executes about 10mm anterior translation; the extreme anterior movement gives the uppermost about 50mm vertical translation, and the hinge movement only opens up to about 20mm vertically; the lateral movement achieves about 12mm at the farthest end. The range of envelope at the deepest point can even reach 700mm in adults in the sagittal plane. These parameters can be used to determine the workspace of the robot and ensure the maximum mandibular movement is inside the jaw robot workspace.

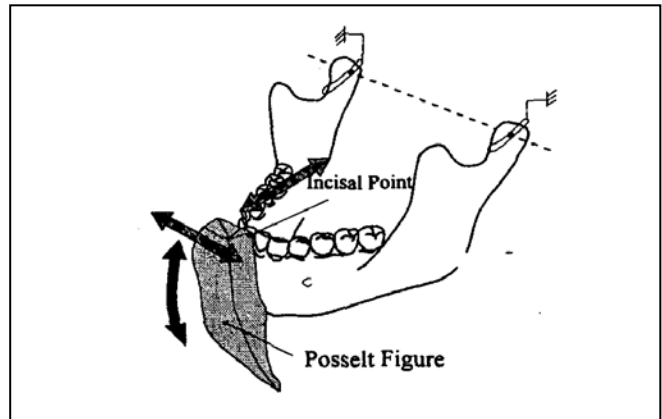


Figure 7. The maximum mandibular movement

After determining the workspace of the robotic exoskeleton, the other specifications could be ensured by clinical studies. The baseline of the limited jaw movement is determined by the incisor movement, which between 20mm to 35mm. As the minimal distance to maintain the functionality of the mandible, 20mm can be set as the least that should be provided by the jaw exoskeleton. Additionally, the forces applied to hold the lower jaw varies with inter-individually amid various circumstances. According to the article, the minimal force to open the jaw is less than 5N but adequate to overcome passive muscle force. A larger force that the mechanism can apply to the lower jaw will be specified within a range between 10N-30N. Besides, a good time setting of the device is also impotent for the rehabilitation purpose, which is reflected the cycle time and speed of chewing cycle. To avoid overtraining and injury in the exercise, time spending in one cycle is specified more than 2s. Consequently, based on the fast chewing cycle consumes around 0.5s, which gives an estimated velocity for 20mm opening around 80mm/s. Table II include the quantitative specification of the robotic exoskeleton.

TABLE II. QUANTITATIVE SPECIFICATIONS OF THE ROBOTIC EXOSKELETON

Items	Specifications
Trajectory	Opening/closing Forward/backward Sideways
Opening directions	Normally 0mm-20mm
	Maximal 55mm
Grinding range	>40mm
Operation Force	Normally 10-40N
	Minimal 5N
Practice Time	>2s a cycle
Operation Speed	<80mm/s
Total weight	<50kg

A multi-DOF manipulator in a parallel form could drive the jaw attached on effector. The flexibility and the workspace of the jaw movement can be easily achieved. According to the ideal human mandible movement, it has 3-DOF that are mouth open and close, forward and backward, and lateral motion. Because of the variation between different patients, a 6-DOF manipulator is necessary to generate the unspecified patient's mandibular movement. The kinematic model of the 6-DOF manipulator illustrates in Figure 8.

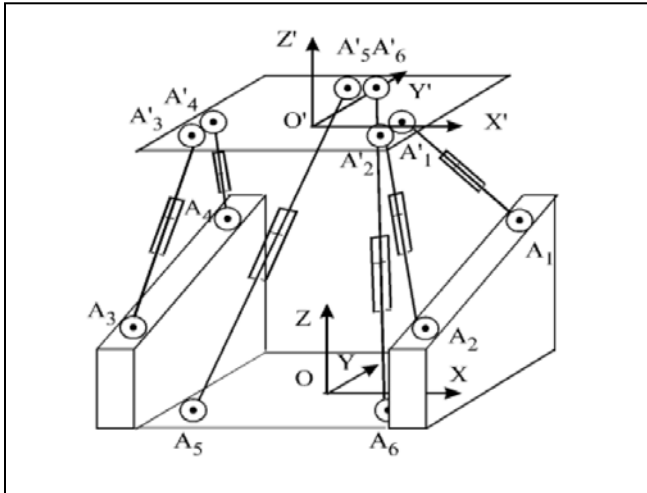


Figure 8. The model of the 6-DOF manipulator

B. The Robotic System Description

An integrated mechatronic system of the robotic exoskeleton consists of three subsystems by hardware implementation that are a mechanical system, the electronic and the sensory subsystem. The specifications of the jaw exoskeleton are achieved by conforming the mechanical subsystem. The electronic subsystem passes the control decision to the actuator based on the feedback acquired from the sensory subsystem. The sensors could detect the real-time status of the robotic exoskeleton movement and acquire the sensor signals to the actuators. The most important factor during training is the force applied by the robotic exoskeleton which acting on the patient via mouth opening. Therefore, a load cell sensor should be used to measure the mouth opening force and at the same time feedback to the system controller. The forward and backward forces should be also acquired by strain gage force sensors. Also, the velocity sensors and position sensors are required in each DOF that correspond to muscle spindle. The mechatronic system of the robotic exoskeleton is illustrated in Figure 9.

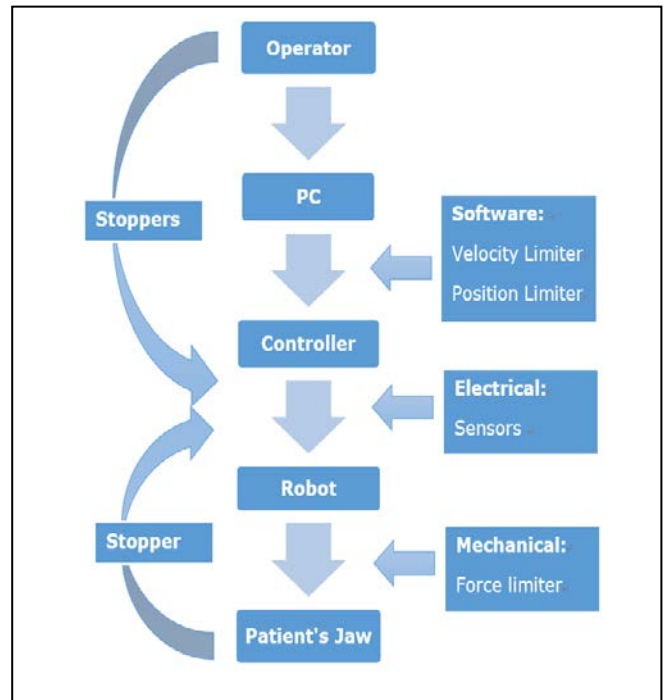


Figure 9. System illustration

The robotic exoskeleton robot has been designed to applied force to patients' jaw. Therefore, the safety features are required to avoid as much as possible for any possible risk to the patient [16]. For that purpose, the consideration of the safety system of the robot should include:

- Two mechanical stoppers
- The electrical stopper
- Software limiters
- Emergency motor stopper for patients

The mechanical stoppers are separate stoppers to protect patients from the training. The one mechanical stopper constraints the motion of the incisor tooth to avoid the excessive mouth opening motion and the other mechanical stopper constraints the TMJ's motion to avoid the excessive motion of the joint. The electrical stopper is implemented into actuators. The software limiters are implemented into the control software of the robot. In particular, the velocity and motion positioning are limited within safety range of operation. Additionally, the operator could input the force threshold before the training. In the case that the force load exceeds a threshold value the robot will be also released to avoid any injury to the patient. Finally, an emergency motor stopper is placed for the patient. Before the training, the operator should confirm that the patient can use the emergency stopper and the function of the stopper is available. It is important to point that, the stopper should hold in the patient's hand because it is the only safety system under the patient's control [13].

IV. CLINICAL APPLICATION OF THE ROBOTIC EXOSKELETON

A. State of the Research in Rehabilitation of TMD

TMD includes a variety of conditions associated with pain and dysfunction of the TMJ and the masticatory muscles. According to the estimation, about 20% of the population is affected to TMD, with 10% to 20% of those seeking treatment [17]. The presenting main symptoms of TMD are (1) intermittent or persistent pain in the masticatory muscles or the TMJ, and less frequently in adjacent structures; (2) limitations or deviations of mandibular movement; and (3) TMJ sounds [2]. These symptoms of TMD may affect the quality

of daily life, with a negative effect on social function, emotional health, and digestive system.

Non-invasive, conservative treatments provide improvement or relief of symptom and are recommended in the initial management of TMD. Physical therapists are frequently involved in the management of TMD, often in collaboration with dental therapists. American Dental Association report that physical therapy was listed among the ten most common treatments used involving 10% to 17% of patients who suffered from TMD [7]. The assumption is that the robotic exoskeleton could be used in the management of the TMD as a more effective joint mobilization tool to replace conventional apparatuses in physical therapy.

B. Clinical Practice, Protocol and Instruments for Rehabilitation of TMD

1) Traditional devices and robotic devices in practice

Jaw movement training with conventional mouth opening apparatuses is commonly used in the clinic environment for temporomandibular disorder (TMD) to rehab the patients who have problems opening and closing their mouths. Conventional mouth opening apparatuses are simply structured such as screws or cones with enlarging diameter, wedge exercisers, elastic traction and hydraulic passive motion devices which shown in Figure 10.

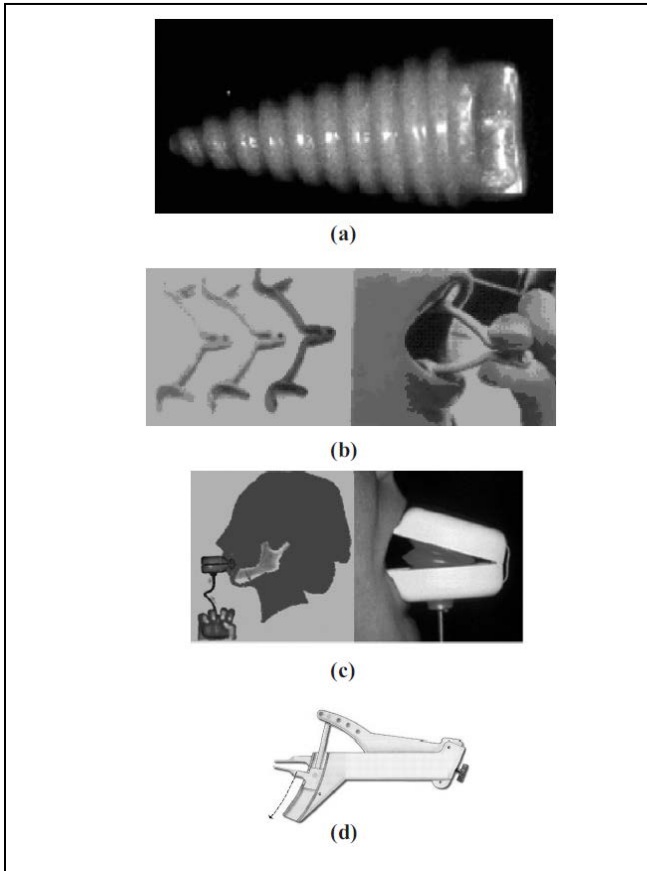


Figure 10. Traditional devices for TMJ rehabilitation

The concerns and disadvantages for these mouth openers include poorly distributed force, intermittent force, damage to the teeth, pressure sores, short-term durability, the need for a preliminary opening, difficult and expensive to fabricate, and the requirement for close clinical supervision [18]. A TMJ exerciser [19] was developed to avoid these disadvantages, and the clinical trial results indicated that this TMJ exerciser is an effective tool for long-term physiotherapy. The CAD model of the TMJ exerciser is shown in

Figure 11. The TMJ exerciser includes a power screw to overcome the small force control difficulty and a U-shape platform which could be inserted to be held by the patients to decrease the mouth loading.

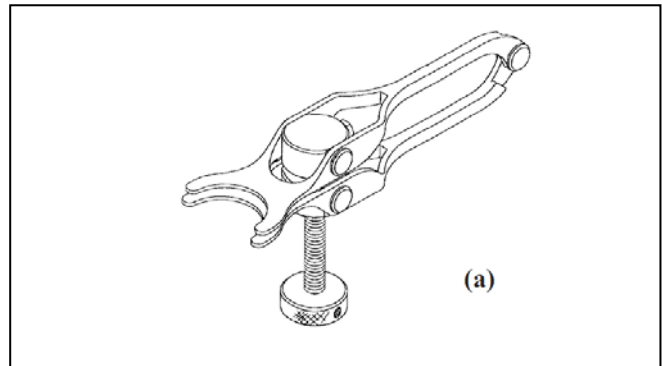


Figure 11. The TMJ exerciser

A Spring-Bite was developed as another newly designed device for jaw motion rehabilitation. This device is characterized by a first class lever mechanism, which allows performing passive jaw motion rehabilitation as a constant load without an active participation by the patient [20]. The Spring-Bite is shown in Figure 12.



Figure 12. The Spring-Bite device

However, these newly designed devices still have shortages due to the deficiency of actuators, sensors, and control system. Therefore, the training with these simple mouth opening apparatuses is based on the doctor's technique through their experiences [4]. Moreover, the significant real-time parameters are unknown during training. Consequently, the data to measure the improvement of the patient could only be the mouth opening distance.

Based on the shortages of conventional mouth opening apparatuses and therapy, jaw rehabilitation robots are developed to improve the disadvantages of conventional apparatuses and increase the training efficiency. Two typical jaw rehabilitation robots for TMD are the WY series robots developed by Waseda University of Japan and the wearable device for rehabilitation of TMD, which developed by Massey University in New Zealand. Their mechanism design and features are described in the literature review. In clinical practices, The WY series robots could be used for mouth opening and closing training and lateral movement training. They also apply a master-slave system for the treatment, and muscular electromyography (EMG) signals are incorporated into the WY robots to react the changes in the patient's jaw. Compared with WY series robots, the wearable robot from Massey University due to the single-DOF linkage is more suitable for the rehabilitation of the neurological TMDs for intensive exercise.

2) Protocol, clinical data and assessment instruments for TMD

Before the rehabilitation, it is the responsibility of every therapist to have an easy to use and safety protocol in place. The therapist is also accountable for ensuring that everyone using the protocol does so it is full extent. Currently, there is a lack of consensus among

researchers regarding the diagnosis and management of this disorder. As a general rule, a diagnosis can be viewed to be useful to measure and to characterize clinical conditions. Although numerous diagnostic systems have been proposed for TMD, only two are currently in wide use, the clinically-oriented American Academy of Orofacial Pain system and The Diagnostic Criteria for Temporomandibular Disorders (DC/TMD) [17]. The DC/TMD applies a dual-axis-system to diagnose and classify patients with TMD. The first axis is divided into three groups of commonly occurring TMDs:

- Muscle disorders, including myofascial pain with and without limited mandibular opening
- Disk displacement with or without reduction or limited mandibular opening
- Arthralgia, arthritis, and arthrosis.

The second axis includes a 31-item questionnaire, used to evaluate relevant behavioral, psychological, and psychosocial factors such as pain status variables, depression, nonspecific physical symptoms, and disability levels [21].

At the same time, a history documentation should be created for the patients and stored when necessary transferred. The document should record the patient's first awareness of the symptoms and every symptom that may relate to the TMD. In addition to keeping written or computerized records of clinical symptoms and history, other methods of record-keeping are available, such as intraoral photographs and plaster models. The clinical data could be measured by a calibrated examination that for the therapists to develop different rehabilitation plans that suit for different patients. This process can be done either on a computer or by keeping a hard copy of an examination sheet. The examination includes TMJ examination, muscle examination, and occlusal examination [22].

It is worth note that in TMJ examination, the range of movement, TMJ tenderness, and joint sounds are the element that should at least be measured. The range of movement should be measured in the vertical and lateral dimensions, which shown in Figure 13. The method of measuring the range of mandibular movement, for example by use of a ruler, a Willis bite gauge or, to be accurate, a Vernier bite gauge. The measurement should not use fingers such as 'two fingers width of opening' as this does not provide sufficiently accurate information.



Figure 13. Measuring the range of movement in the vertical and lateral dimensions

The best way of examining the joints for tenderness is by palpation via the external auditory meatus and then asking the patient to open and close the mouth gently. The illustration shows in Figure 14.

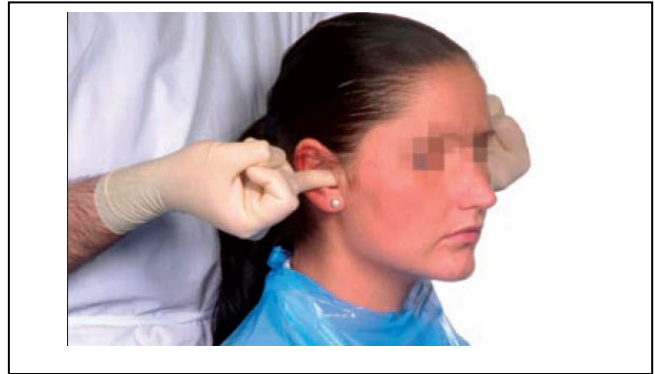


Figure 14. The best way of examining the joints

The disc and capsule of the TMJ have a poor nerve supply. The posterior bilaminar zone, however, is highly innervated. If there is disc displacement, this area inevitably becomes stretched and may become interposed between the head of the condyle and the fossa of the temporal bone that can lead to painful clicking and cause discomfort.

Joint sounds should be detected with a stereo stethoscope ideally (Figure 15). Note should be made of whether the click is painful or painless, single or multiple and early or late in the opening or closing cycle.



Figure 15. Joint sounds can be detected with a stereo stethoscope

Examination of the range of movement, joint sounds, signs of bruxism, joint and muscle tenderness and occlusion should take the therapist no more than two or three minutes to perform and it is their duty to do this for all patients as a prerequisite before robotic rehabilitation. It is important for the dentist to record that pain, muscle, and joint tenderness are subjective in their severity. What may be severe to one patient may not be to another. It is noteworthy that the only true measurable parameter of whether or not the patient's condition is improving the range of movement.

3) Use of the Robotic Exoskeleton in the Rehabilitation of TMD

The TMJ rehabilitation robot refer to therapeutic robot which has the features that it used by multiple users, for short-term training and under medical supervision. Although the robotic exoskeleton for

TMD has been confirmed its efficiency and ability in rehabilitation therapy, multidimensional factors like costs, safety, legal issues, regulations, enabling technologies and acceptance will play key roles in the popularization of the clinical environment [23,24].

In the case of TMJ robotic rehabilitation, merits and demerits of the rehabilitation robot training that have been statistically collected as evidence provide the most important information for decisions regarding future treatments. The residual risk, which is the risk remaining after protective measures have been taken, must be fully understood by both therapists and patients before the training. In addition, if the users still do not want to try to use the robotic rehabilitation after being informed of the residual risk, the training must be abandoned.

V. CONCLUSION

In conclusion, the robotic exoskeleton was developed based on the properties of the human mandible biological system and the general requirements for the rehabilitation training. The robotic system involved three subsystems which are mechanical subsystem, electronic subsystem, and sensory subsystem. Meanwhile, the safety issues were considered into the robotic system. The stoppers and software limiters were required in the safety system. The clinical applications were discussed in this paper, including both traditional and robotic devices for TMD rehabilitation, the protocols for TMD diagnostic, the examination before rehabilitation and the documentation for patients. Although there is evidence to show that the robotic training is efficient for patients, but to introduce the robotic exoskeleton into the clinical environment, many factors still need to be considered.

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