2011 International Conference on Computer Control and Automation (ICCCA 2011)

A Study of Rotary-Brake Design for Utilizing in Motorized Upper Limb Prosthesis

Wirawat Sirisopha[1], Jackrit Suthakorn[2,*]
Department of Biomedical Engineering
Mahidol University
Nakorn Pathom, Thailand
[1]wirawat@bartlab.org, [2,*]egjst@mahidol.ac.th

***Abstract*—A number of motorized upper limb prosthesis has been investigated and developed in recent years with several new technologies; reach and grasp an object at the same time with water-resistant electric terminal device in Utah arm, audible and vibratory feedback in Boston digital arm, thought-controlled for patients who have undergone TMR surgery in Otto Bock's dynamic arm, for instance. However, an important problem found in elbow parts of those prostheses, is power constraint. The reason is occurred when amputee requires to move their prosthesis arm to a desired position or to lock an elbow to hold an object. The power is drained and consumed for the arm's motion control. Such the prosthesis requires more energy, therefore, the power storage, weight and cost are needed to be increased. To solve these problems, a new brake/clutch system has been studied and designed for consuming less energy but provides suitable torque, and two-directional rotation which works similar to other electric motors. Therefore, the purpose of this study is to demonstrate a new design of our brake/clutch system that can work in two directions as a normal-hinge joint as seen in general prosthesis products.**

Keywords- Non-backdrivable mechanism, Sprag clutch, Motorized prosthesis, Elbow.

I. INTRODUCTION

Upper-limb prosthesis has been developed for many years to reach the requirements of lightweight, inexpensive, fitted to the user, cosmetic purpose, and saving energy. The generations of upper limb prosthesis [1-3] start from using simple Bowden cable as a pulley to control arm movement then developed to use pneumatic and then comes up with an externally powered prosthesis with portable batteries, electronic circuit, and small electric motors. As described, the upper limb prosthesis can be separated into two groups [4] which are passive and active. The example of passive prosthesis is kind of prostheses for cosmetic purpose. Another example, the active prosthesis is more functional which can be divided to body-powered and externally-powered prosthesis. The body-powered prosthesis is controlled by the motion of body joint from muscle and tendons. The externally-powered prosthesis is controlled by muscle signal and powered by batteries. Nowadays, most commercial upper limb prostheses are powered by external energy called the myoelectric prosthesis. The present myoelectric prostheses are consists of the Boston Elbow, Utah artificial arm, and Otto Bock dynamic hand. Myoelectric prosthesis is using electrical signals to control the arm movement such as elbow flexion and extension, wrist rotation, and hand grasping. The electric signal will come from muscle, which has been innervated, pass through the electrode on the skin, electrode inside the prosthetic socket, and finally to the prosthesis. From the commercial myoelectric prostheses [5,6] as shown above, there are different advantages such as; the elbow can be automatic locked in every desired angle; High speed movement; and good responsive control. Due to the prosthesis from developing countries and worldwide commercial, the commercial prostheses were use motorized structure and more function usage but expensive. However, the prosthesis from developing countries is cheap but simple usage function and simple hinge structure. Therefore, the idea is that we can develop a cheap, motorized structure with more usage function of prosthesis for developing countries.

The motorized prosthesis consists of many parts such as motor, gear, material, and brake which each part are affecting in different type of usage. From the study, we will consider the brake in an elbow part. The reasons for considering in elbow part by designing brake/clutch instead of normal hinge joint are (1) to reduce energy consumption during elbow movement of holding and locking; (2) let the prosthesis more efficient; and (3) to reduce weight and cost. The elbow joint is including two motions of flexion and extension. By these movement, the joint which controlled by hinge joint can be moved in both directions of flexion and extension. Therefore, the objectives of this study are to demonstrate that the designed clutch, which used in the elbow part, can moved in two directions of flexion-extension like a normal hinge joint as seen in today prosthesis and reach the goal of energy consumption in the prosthesis.

Normally, today's application of brake and clutch type consist of many types such as band brake, one-way clutch (wrap spring, roller, and sprag), particle brake/clutch, etc. From the clutch types above, each brake and clutch type have their own strong and weak points as shown in table.1 [7]. Torque density is limited by torque of 1Newton maximum and weight less than 30 gram due to the required specification for the objectives about lightweight. From table.1, we can define that sprag clutch and roller clutch is both suitable to the study because of torque density however sprag clutch is cheaper and gave maximum torque density better than roller clutch. Therefore, the sprag clutch will be the choice in the study.

TABLE I. COMPARISON OF BRAKE AND CLUTCH TYPES

Types	Strong	Weak

Types	Strong	Weak
Band brake	- Simple and cheap	- Wear occurred during working
Particle brake	- Rotor and shaft spin freely when coil energized	- Torque density is 0.002 Nm/g
Wrap spring clutch	- Low cost - Non slip or getting backward due to one directional movement	- Torque density is 0.00623 Nm/g
Roller clutch	- Simple design - Free spin in one direction and lock in opposite direction - Torque density is 0.15 Nm/g	
Sprag clutch	- Low cost - Simple design - Maximum torque density is better than roller clutch	- Need lubricant

Torque density is torque (Nm) per weight (g)

In this study, we will create a conceptual design and simulation of sprag clutch by SolidWorks software. This conceptual design will solve the objective of the study. Section 2 will show the previous works and on-going research of motorized upper limb prosthesis. Section 3 will describe structure, mechanism, and methods of the sprag clutch. Section 4 and section 5 will show the conceptual design and preliminary result from testing the sprag clutch respectively.

II. Previous works

From both on-going research and commercial products, there are many works which are motorized type of upper limb prosthesis. The examples are show as follow: (a) Utah Artificial arm [8,9] which developed by the Motion Control comes with many new features such as high-speed movement, good responsive control of an elbow, and more natural movement in simultaneous elbow and hand control. This arm can drive an elbow up to 22 desired positions by DC motor and also can hold loads up to 22.7 kilogram (50 pounds) but the weak things are consumed lots of energy and heavy due to the external batteries; (b) Boston Digital arm [10,11], the first Myoelectric controlled elbow, manufactured by Liberating Technologies (LTI) with a platform for controlling various devices such as hands, grippers, wrist rotators, and shoulder lock actuators. This arm is use sprag type clutch as a motor to drive the arm in both flexion-extension direction and can be locked in every position as soon as the motor not powered; (c) Otto Bock Dynamic arm [5], developed to use with transhumeral and shoulder disarticulation amputees, is lower battery weights and faster than other elbows prosthesis because the use of a variable gear mechanism; (d) Touch Bionics I-limb hand [12,13], the first commercial available bionic hand which looks and acts like a real human hand, is the multi-articulating finger which each finger can be automatically locked into desired position when pressing finger against a firm surface which controlled by patient's limb muscle signal through separated motor.

III. Materials and method

A. Sprag structure and Mechanism

For one sprag clutch, it consists of three main parts: inner and outer race, sprag, and spring. Figure 1 has shown the structure of the sprag clutch. The outer race and inner race are use to arrange the sprag into the line for uniform torque transmission. The sprag which placed between inner and outer race is use to transmit torque during engagement. The spring is use to prevent clutch from backlash during the operation and use to hold the sprag in a position. For some kinds of sprag clutch, they use cages as an extra structure which used to separate sprag out to reduce friction and make faster engagement.

The mechanism of normal sprag clutch is starting when if we put the force to run an inner race in anti-clockwise direction and fix outer race, the clutch will turn freely in anti-clockwise direction and locked in the opposite direction by the sprag as shown in figure 2 [14]. From the mechanism will created the torque transmission in locked direction and no torque transmission in freely rotation.

B. Method

There are many methods that related with sprag clutch designation such as Tanaka et al. [15] have used methods of finite element and two-dimensional theory of elasticity to analyses the self-locking characteristics of one-way clutch; Controzzi et al. [16] used non-backdrivable mechanism, based on wedge phenomenon in their SmartHand, to see the possibility of no energy consumption when transmitted torque. To see the efficiency and performance of the system,

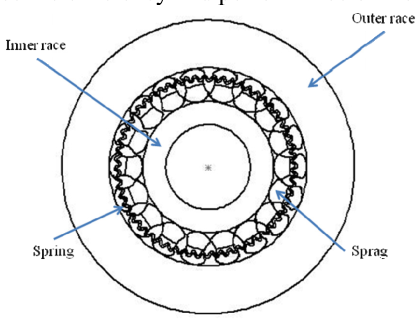

Figure 1. Sprag clutch structures

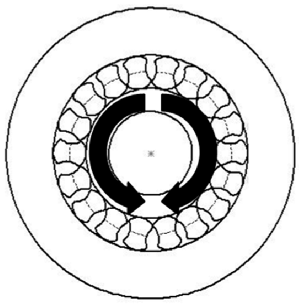

Figure 2. Sprag clutch mechanism

they used kinematics, static, and dynamic analysis to evaluate it; W.C. Orthwein [17] used simple equilibrium equation and trigonometry identity to solve the curvature of the sprag. From the description, the related sprag clutch method will describe briefly as follow.

1) Contact forces

The contact forces of the sprag clutch can be calculated by the geometry of forces from summing the forces which acted on the sprag surface between inner and outer race to the x-y axis which given by equilibrium equation in (1) and (2).

$$\Sigma F_x = 0 \tag{1}$$

$$\Sigma F_y = 0 \tag{2}$$

2) Sprag geometry

The sprag geometry is the calculations which use to define the radius of curvature of sprag clutch by using the equilibrium equation which mentioned above. At the beginning, we have to calculate the moment equilibrium equation of the sprag about the axis of rotation of the clutch as shown in (3) by summing the forces in the direction of the friction forces between the contact surface of the sprags and the outer race.

$$\mu_o F_o r_o - \mu_i F_i r_i = 0 \tag{3}$$

Which μ_o and μ_i are the corresponding coefficients of friction, F_o and F_i are refer to the normal forces, r_o is radius of outer race, and r_i is radius of inner race.

We can found the angle α which subtended by the sprag at the center of the clutch as shown in figure 3 from substituting the normal forces into the moment equilibrium equation of sprag and also the trigonometric identity of (4).

$$\sin^2\alpha + \cos^2\alpha = 1 \tag{4}$$

Finally, substituting r_s, r_i and r_o, which r_s is radius of sprag contact surface, into finite element program for contact stress at the inner and outer radii. To find the minimum radius of curvature r_s that will give a permissible stress for these sprag profiles for the inner race and for the outer races.

3) Non-backdrivable mechanism

The non-backdrivable mechanism (NBDM) is the mechanism which will make the device will not move when the actuators are not powered and will move freely when the actuators are powered. NBDM mechanism can transmit motion only from the input to the output axis and not vice-versa.[1] Figure 4 will describe the NBDM with the conceptual design of this study. When the input (1) is rotated clockwise and anti-clockwise will lead the sprags (2) engaging and lead the output (3) to rotate anti-clockwise and clockwise respectively. However, if the input (1) stopped the output (3) will be locked by the sprag itself.

4) Finite Element Analysis

According to the objective of the study, the finite element analysis (FEA) is used to demonstrate the sprag clutch to

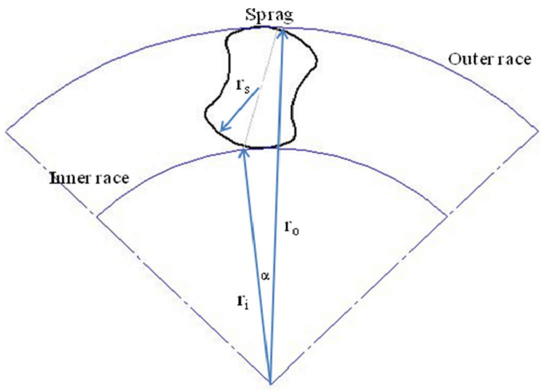

Figure 3. Sprag geometry

rotate into two directions by simulate the conceptual design of sprag clutch in SolidWorks software.

IV. Preliminary Result

According to the proposed of the study, the sprag clutch need to run in to two directions which a mechanism is the output will move either way when input is running and output will not move when input stop. From the mention mechanism will effects to the prosthesis arm to lock if motor stopped and move when motor is running. The designed sprag clutch was tested by SolidWorks software and simulated in four tests; a) Rotate input in clockwise direction and let the output rotate anti-clockwise; b) Rotate input in anti-clockwise and let the output rotate clockwise; c) Input stop and let the output rotate clockwise; d) Input stop and let the output rotate anti-clockwise. The torque of 1 Newton-meter was applied to run the inner race and outer race to represent the movement of input motor and the output of the prosthesis arm. Figure 5 shows the displacement results of the designed sprag clutch which dark-blue areas represent no movement, while red areas represent the most movement during the simulation. Therefore, this study has been considered that it can be use as two-directional clutch with non-backdrivable mechanism.

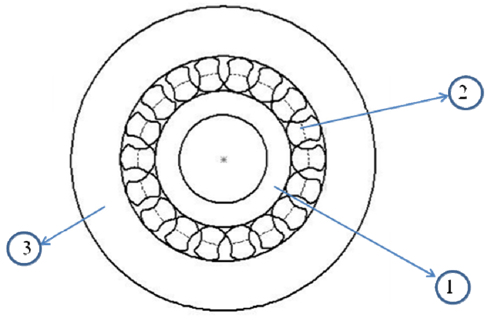

Figure 4. Non-backdrivable mechanism

[1] M. Controzzi, C. Cipriani, and M. C. Carrozza, "Miniaturized non-back-drivable mechanism for robotic applications," Mechanism and Machine Theory, vol. 45, pp. 1395-1406, 2010, doi 10.1016/j.mechmachtheory.2010.05.008, in press

V. Discussion

This paper discussed a preliminary design of sprag clutch to use with prosthesis arm which reached the ideas of two directions movement and lightweight. The approach for this paper was using non-backdrivable mechanism and finite element analysis. The conclusion for this preliminary design of sprag clutch is seems to be rotate in two directions with non-backdrivable. However, this design sprag clutch has not been tested in any physical experiment. The author plans to fabricate the designed clutch and test the compatibility with the prosthesis arm.

Acknowledgment

The author wish to thanks Prof. Dr. Jonathon W. Sensinger from Northwestern University for his invaluable helps. The author also would like to thank Center for Biomedical and Robotics Technology lab (BART LAB), Mahidol University for all facilities affords.

References

[1] P. D. Dudley S. Childress, "Historical Aspects of Powered Limb Prosthese," *Journal of Prosthetics & Orthotics,* vol. 9, pp. 2-13, 1985.

[2] P. D. Harold H. Sears, "Special Considerations:Trends in Upper-Extremity Prosthetics Development," in *Atlas of Limb Prosthetics: Surgical, Prosthetic, and Rehabilitation Principles*, 2nd ed Rosemont, IL: American Academy of Orthopedic Surgeons, 1992.

[3] R. F.ff.Weir and J. W. Sensinger, Standard handbook of biomedical engineering and design: The design of aritificial arms and hands for prosthetic applications.

[4] C. Lake and R. Dodson, "Progressive upper limb prosthetics," *Physical Medicine and Rehabilitation Clinics of North America,* vol. 17, pp. 49-72, 2006.

[5] R. J. Sobotka, "The Use of Myoelectric Control in Upper Extremity Prostheses." http://www.ballert-op.com/myoelectric_control.asp.

[6] S. C. Jacobsen, D. F. Knutti, R. T. Johnson, and H. H. Sears, "Development of the Utah artificial arm," IEEE Transactions on Biomedical Engineering, vol. 29, pp. 249-269, 1982.

[7] G. M. Roach and L. L. Howell, "Evaluation and Comparison of Alternative Compliant Overrunning Clutch Designs," *Journal of Mechanical Design,* vol. 124, pp. 485-491, 2002.

[8] E. Iversen, H. H. Sears, and S. C. Jacobsen, "Applications of control: Artificial arms evolve from robots, or vice versa?," in *IEEE Control Systems Magazine*. vol. 25, 2005, pp. 16-20.

[9] S. C. Jacobsen, D. F. Knutti, R. T. Johnson, and H. H. Sears, "Development of the Utah artificial arm," *IEEE Transactions on Biomedical Engineering,* vol. 29, pp. 249-269, 1982.

[10] "Boston Digital Arm™ System." http://www.liberatingtech.com/products/LTI_Boston_Arm_Systems.asp.

[11] C. Toledo, L. Leija, R. Munoz, A. Vera, and A. Ramirez, "Upper limb prostheses for amputations above elbow: A review," in *Health Care Exchanges, 2009. PAHCE 2009. Pan American*, 2009, pp. 104-108.

[12] C. Connolly, "Prosthetic hands from Touch Bionics," *Industrial Robot,* vol. 35, pp. 290-293, 2008.

[13] M. Fairley, "State-of-the-Art Upper-Limb Prosthetics Technology," The O&P EDGE, 2009.

[14] D. Brooksbank, "Autorotation is a Sprag Thing," in *Rotor & Wing*, 2010., article in a magazize

[15] T. Michihiko, S. Shuji, F. Takahiro, and M. Hideo, "Fundamental Studies on the Self-locking Characteristics of Oneway Clutch," Bulletin of JSME, vol. 24, pp. 2154-2161, 1981-12 1981.

[16] M. Controzzi, C. Cipriani, and M. C. Carrozza, "Miniaturized non-back-drivable mechanism for robotic applications," *Mechanism and Machine Theory,* vol. 45, pp. 1395-1406, 2010, doi 10.1016/j.mechmachtheory.2010.05.008, in press

[17] W. C. Orthwein, "Clutches and Brakes Design and Selection," 2nd ed *New York*: Marcel Dekker, Inc, 1986.

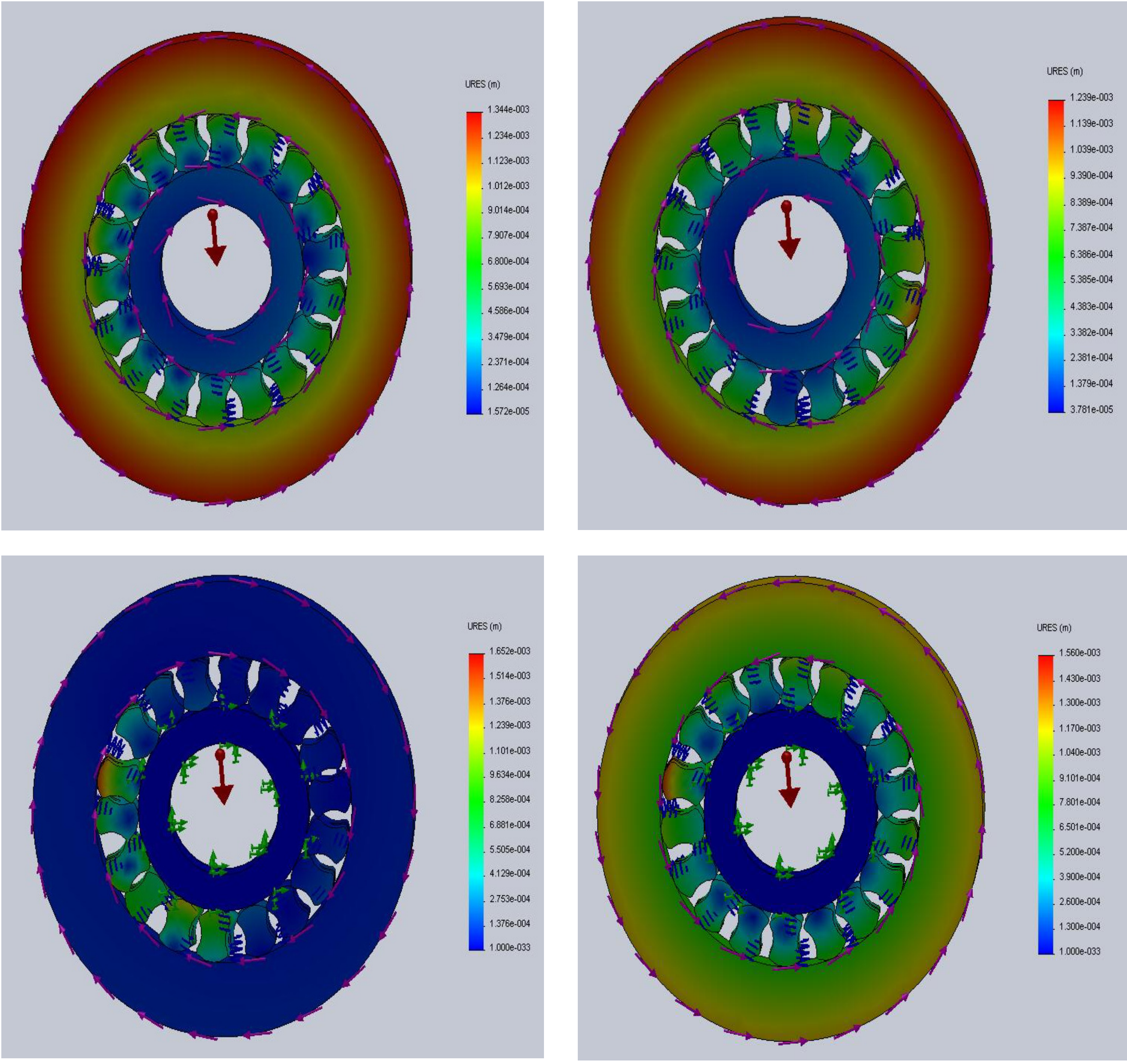

Figure 5. FEA of sprag clutch in different movements; Input rotate clockwise while output rotate anti-clockwise. (Top left); Input rotate anti-clockwise while output rotate clockwise. (Top right); Output rotate clockwise while input stopped. (Bottom left); Output rotate anti-clockwise while input stopped. (Bottom right)