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Design and Development: Actuator of Powered Knee Orthosis a Prototype

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Abstract — **Recent technological advances has made knee orthosis to become a robotic device known as powered knee orthosis (PKO). This paper describes the design and development of PKO which have high torque and high back-drive-ability. Both criteria are the most important things in designing a PKO to avoid control issues. There are many existing design of PKO, especially the main part of the design which is knee actuator. Outrunner type of brushless DC motor (BLDCM) as an actuator was used to give an external power to the user during knee flexion or extension. This device capable of assisting knee movement but feels transparent during movement. Simple preliminary shank lifting experiment tested on one healthy subject, was conducted and observed. Thus the approached PKO can lift the subject's leg during actuator on with highly back drivable during actuator off.**

Index Terms — Knee orthosis, Powered Knee orthosis, Actuator design of knee orthosis, Lower Limb Exoskeleton

I. INTRODUCTION

In the past ten years, wearable lower limb powered orthosis have been developed with an objectives of augmenting human power, supporting heavy load, assisting walking and rehabilitation of disabled people. Researchers have developed many innovative and interesting design to assist lower limb movement. Some of research groups have been developed lower limb powered orthosis using electric motor, hydraulic and pneumatic. All of the researches effort has been reviewed in [1]–[5].

Due to the bulky size, heavyweight and high complexity features of hydraulic and pneumatic, compare to electric motor that offer compact, lightweight and low complexity features, it is much more popular among the researcher these day, suitable to use as knee actuator, and offer a better future development as the electrical technologies expand quite fast than hydraulic and pneumatic technologies. As evidence, most commercialize exoskeleton these day such as HAL [6] and Vanderbilt [7] using electric motor for joint actuation.

Lower limb powered orthosis involves 3 joints; hip, knee and ankle. Focusing on knee, most of powered knee orthosis actuated by using brushless DC motor (BLDCM) [6]–[10] and rarely actuated by using brushed DC motor (BDCM) as did in [11]. This is due to several advantages of BLDCM compared to BDCM, such as higher efficiency, high output power, high speed range, more torque density, can be made in flat shape and much more.

Normally, BLDCM alone cannot actuate the shank due to insufficient torque. Hence, gearbox that has certain gear ratio must be used to amplify the motor torque. Many design has been made regarding the implementation of BLDCM with gearbox on knee orthosis, as written in [6]–[13]. Most of authors used BLDCM with a ready-made gear box. For BLDCM type, some of them used outrunner type and some others used inrunner type. The types of gearbox that commonly coupled with BLDCM are harmonic gear drive. Due to actuator design complexity, harmonic gear drive is preferable because it can be made flat, easy to implement, compact and can give a very high impact on gear ratio, as used in [6], [12], [14]. With both flat; BLDCM and gearbox, a small volume on the side of the leg can be maintained.

In addition, one thing that need to be consider when using a high gear ratio is back-drive-ability of the actuator. Back-drive-ability or also known as is generally defined as the capability which a motor or gear motor can be driven by its attached load when power is remove from the motor. The ability of the motor to back driven is depend on the gear ratio and the efficiency of the gear. The higher the gear ratio the higher the mechanical impedance resulting the more torque it takes to back-drive the gear motor. Actuator with a non-back-drivable transmission will bring to safety and control issues. Some of the researcher countered those issues by using Bowden-cable-driven series elastic actuator (BCD-SEA) used in [15], series elastic actuator (SEA) [9], variable stiffness actuator (VSA) [16], admittance control as in [12], [17] or known as impedance control, and joint-level controller as approached in [18]. All about the characteristic and type of actuator impedance has been reviewed in [19].

The purpose of this paper is to design and develop PKO which have high back-drive-ability but yet can produce high torque without using any controller and complex design of actuator; using only outrunner type of BLDCM and planetary gearbox. This paper will shows how approached PKO's simple design allows it to exert required torque and back drivable during actuator off. This innovative design idea will lead toward a better PKO.

II. METHODOLOGY

A. Hardware Design and Development

The approached PKO design is lightweight. The total weight of approached PKO is 1.2 kg. It is conceived as a single leg orthosis device with one Degree of Freedom (DoF), in which knee are active joint and designed to move only at sagittal plane. At the early stage of the design, the structure of PKO are 3D printed by using polylactic acid (PLA) and are primarily used at the surface structure to reduce weight, while aluminum are used inside of the structure as a frame to account for mechanical resistance.

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The mechanical structure of PKO's knee joint are designed to allow passive movement on sagittal plane, although the PKO's knee joint actually is an active joint. This meant the approached PKO is highly back drivable. The movement of knee joint is mechanically limited to avoid potential damage to the user as shown in Fig. 1and the angle joint movement are shown in TABLE. I

TABLE. I Angle Joint Movement

Knee Joint Movement	Maximum Angle (°)
Flexion	90°
Extension	0°

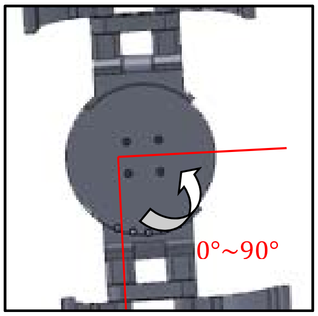
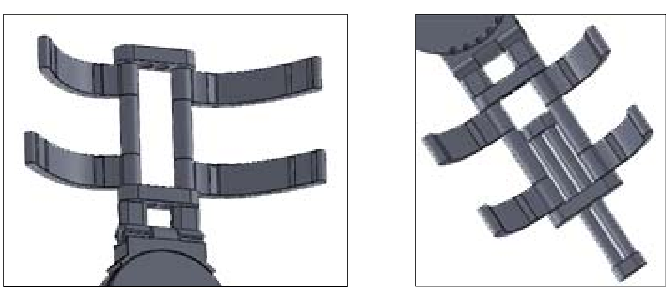


Fig. 1 Knee Joint – Mechanical Limit at 0° and 90°.

Fig. 2 depicts the details about the adjustment of the PKO link joint. The length of the thigh link is fix while the shank link can be adjusted by aluminum frame which can be slide and tightened by a bolt to hold the aluminum frame. The adjustable length of shank link is flexible to any length of user's leg. At the end of sliding aluminum frame was provided for future development of the ankle foot which not highlighted in this paper. Due to the muscle size of shank and thigh, the thigh and the shank links of PKO are made flexible to the size of muscle. This flexibility also designed for the bone structure of the leg. The range of flexibility angle is also mechanically limit to avoid becoming too flexible as shown in Fig. 3. The maximum flexibility angle are shown in TABLE. II.

TABLE. II Maximum Flexibility Angle

Flexibility Movement	Maximum Angle (°)
Outward	45°
Inward	45°



a) Thigh Link b) Shank Link

Fig. 2 PKO Link Joints.

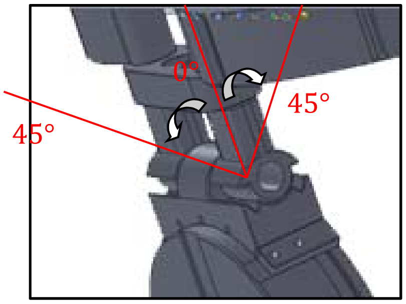


Fig. 3 Flexible Link Joint

The adjustable clamp-shape carriers with Velcro straps allow for customization to individual requirement due to the muscle size. The position of the clamp-shape carriers are fixed and can be rotate only at z-axis. Fig. 4 shows a complete design of approached PKO.

Fig. 4 Complete Design of Approached PKO

B. Knee Actuator

The design and selection of the actuator were based on previous researches [6], [12], [14]. Due to the motor characteristic of necessary power efficiency, high torque, compact in size, flat in shape and portable for wearable devices, BLDCM is found to be very suitable and promises a better future development. In this paper, approach PKO will be used GB90-1 BLDCM outrunner type as knee actuator, having a maximum torque of 0.98 Nm, 22V rated voltage, 90 mm in diameter and sensorless.

A single stage planetary gearbox was designed to attach with the GB90-1 BLDCM. At first, outrunner type of BLDCM must change into inrunner type mechanically by attaching a gear shaft through a hole at the center of BLDCM as viewed in Fig. 5. In this paper, planetary gear was chosen due to flexibility in term of gear ratio. For example; for a fixed diameter of planetary gearbox, gear reduction ratio can be increase by add up a multi stage of gear. This flexibility can facilitate the design adjustment work for torque requirement in future development. Although a harmonic gearbox is more preferable and give a greater gear reduction ratio, it is hard to design, very costly and gear reduction ratio is fixed for a fixed diameter. Most importantly the harmonic gear drive is not back drivable [12] compare to planetary gear.

Fig. 5 Knee Actuator: OBDCM attach to a Single Layer planetary Gearbox

Fig. 6 depicts the explode view of Knee actuator single stage planetary gearbox with 6:1 gear reduction ratio. The methodology in designing an actuator for this paper is:

“For a predetermined output torque, raising the max input torque can decrease the gear reduction ratio of planetary gear drive and hence increase the back-drive-ability of the actuator, otherwise decrease the max input torque will increase the gear reduction ratio of planetary gear drive and hence decrease the back-drive-ability of the actuator”

Since maximum input torque of the actuator is 0.98Nm (refer from BLDCM manufacturing record), hence only single stage planetary gearbox with 6:1 gear reduction ratio is needed. Thus, the maximum output torque of approach PKO is 5.88Nm.

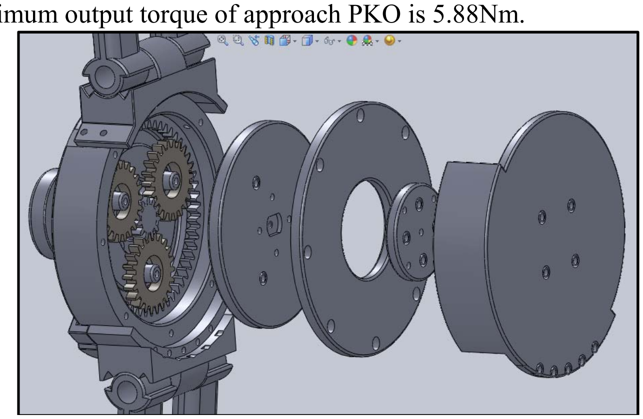


Fig. 6 Explode View of Knee Actuator Single Layer Planetary Gearbox

C. Power System

Fig. 7 indicate the motor joint are driven by an integrated circuit (IC) of L6234. It is a pulse width modulation (PWM) three phase motor drive designed to drive a brushless DC motors at high switching frequency and has no input for sensors feedback. It is very suitable to control a sensorless BLDCM. Arduino nano with a potentiometer as input was used to control PWM to the motor drive. By using potentiometer, clockwise and anticlockwise movement of the motor joint can be control. DC power supply capable of supplying a maximum voltage and current at 30V and 3A respectively, was used.

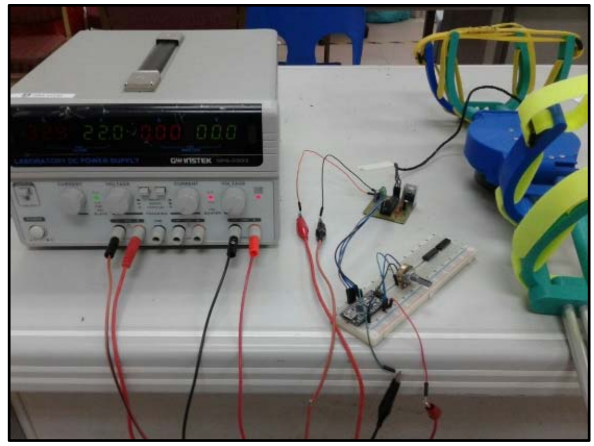


Fig. 7 Overall of Power System

D. Experimental Setup: Preliminary

A simple preliminary shank lifting experiment was tested on one healthy subject as shown in Fig. 8. This experiment is designed to test for the capability of the approached PKO to actuate the knee joint and back drivable. The experiment was setup in the gait analysis laboratory with VICON technology. Subject must wear the approached PKO and stand with one leg on a walkway stage that slightly higher than the ground. The other leg are told to be in relax condition. The Subject has a total body weight of 60kg and 160cm tall. Based from Anthropometric data calculation, the shank weight and length of the subject is 2.79kg and 14.76cm respectively. Three markers are placed at the thigh link, the center of the actuator and the shank link. The flexion angle was measured using VICON gait analysis system.

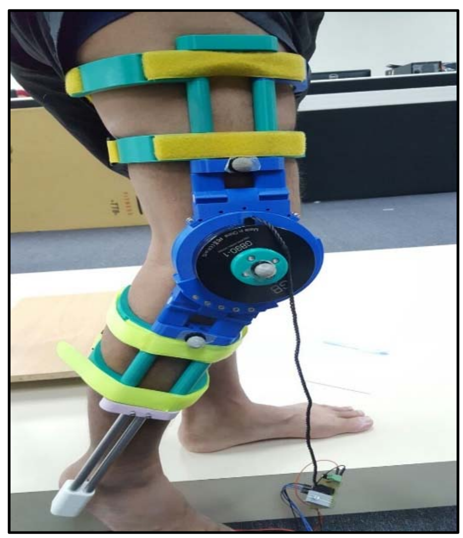


Fig. 8 A Simple Preliminary Shank Lifting Experimental Setup

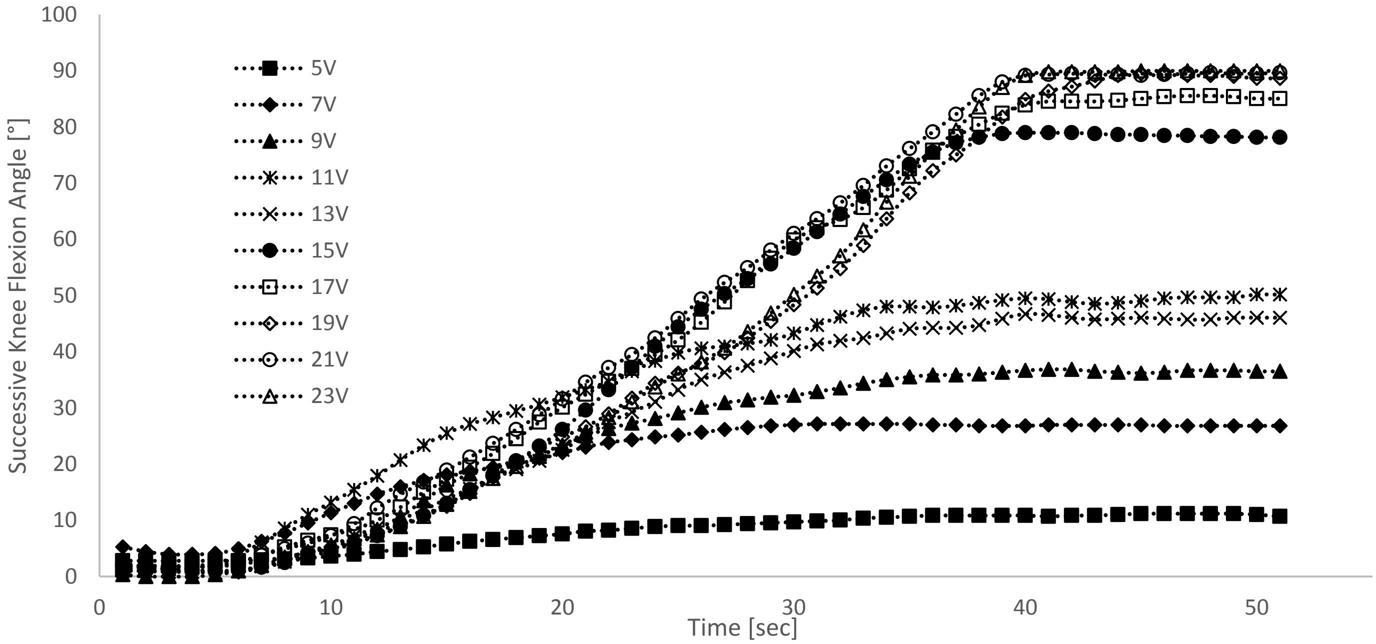


Fig. 9 Knee Flexion Angle vs Time

III. RESULT AND DISCUSSION

The voltage for the actuator was increased from 5V to 23V with 2V increment. The knee flexion angle was measured, recorded and plotted by VICON technology as shown in Fig. 9. The start and end of flexion angle of each voltage increment were recorded in TABLE. III. The starting knee angle was not from 0° due to the experiment procedure where the subject was standing at only one leg while the leg which attached with PKO was kept hanging as possible. The time recorded was referred from the Vicon technology recording time.

Fig. 9 shows the knee flexion angle achieved by the PKO. The PWM signal from Arduino Nano gradually rotate the BLDCM until reached its capability to lift the subject's shank. The successive knee flexion angle increased as the increasing of the voltage supply to the PKO. The minimum and maximum knee flexion angle was at 8.39° (5V) and 88.35° (23V) respectively. The summary of successive knee flexion angle can be seen in TABLE. III. The safety features of mechanical limit of the PKO has limit the successive knee flexion angle from 0° to 90° only.

As from the subject Antromometric data, the calculation of the required torque was done by using Equation 1. The maximum calculated required torque was 4.12Nm when the successive knee flexion angle was at 90°. Fig. 10 shows the voltage supply is proportional to the successive knee flexion angle. The result indicate that the proposed FKO is capable to lift the subject's shank until successive knee flexion angle reached 90°.

$$Torque\ (T) = rFsin\theta \qquad (1)$$

whereby the following notation was used:

- r: shank length
- F: shank mass in Newton
- Θ: successive knee flexion angle

In order to assist gait, the successive knee flexion angle should reached maximum at 60°. The result in Fig. 10 shows that at 15V voltage supply is suitable to assist subject's knee during gait locomotion. The result has shown BLDCM that attached with a single layer planter gear has the capability to assist knee flexion angle while maintain the back drive ability of the BLDCM during gait locomotion.

Future improvement is needed by adding one more gear stage to the planetary gearbox and hence the gear reduction ratio will increase up to 36:1. This will make the maximum torque increase up to 35.28Nm. The increasing of gear reduction ratio also will decrease the degree resolution per step of BLDCM and cause the actuation move in higher precision angle.

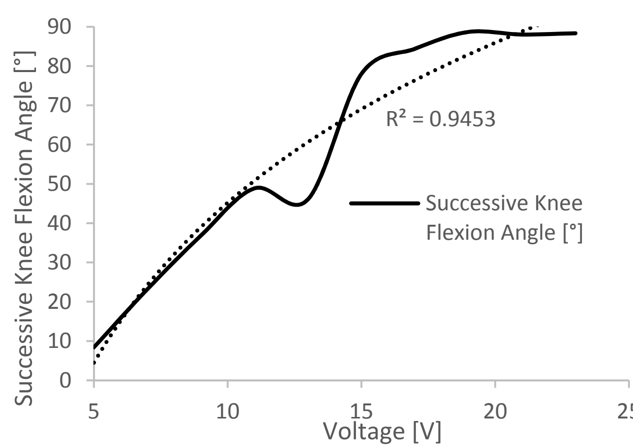


Fig. 10 Successive Knee Flexion Angle vs Voltage

TABLE. III Start and End of Flexion Angle of Each Voltage Increment.

Voltage (V)	Knee Angle (°) Start	End	End – Start (Successive)
5	2.797	11.188	8.391
7	3.948	27.148	23.199
9	0	36.855	36.855
11	1.316	50.182	48.866
13	0.658	46.727	46.069
15	0.987	78.976	77.989
17	1.151	85.557	84.405
19	0.822	89.506	88.683
21	1.645	89.670	88.025
23	1.645	90	88.354

IV. CONCLUSION

Design and development of approached PKO has been presented with the aim to make the approached PKO back drivable but yet high in torque. BLDCM has been choose as an actuator, since it promises a better torque than BDCM. Result from the preliminary shank lifting experiment shows that the approached PKO can lift the shank very well although the max torque is 5.88 Nm.

Further improvement on actuator torque of approached PKO is needed by adding one more stage to the planetary gearbox. Since the gear reduction ratio is only 6:1, the back-drive ability of approached PKO was maintained.

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