Energy Storage and Reversible Mechanisms for Lower Limb Exoskeleton.

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***Abstract*—This study presents a lower limb exoskeleton developed to assist or rehabilitate the physically challenged person who has lost their mobility due to SCI. In order to overcome energy-storing issues related to existing designs, the device uses a spring and camshaft system which is integrated with the robot structure to reduce the required energy by absorbing the bodyweight into spring potential energy and released by the cam design. The design of this work is adapted to match the nationality of Thai people such as a robot's model and walking behavior. Spring and camshaft system is integrated with the robot structure to reduce the required energy by absorbing the bodyweight into spring potential energy and released by the cam design.**

***Index Terms*—Brain-Computer Interface, exoskeleton, lower limb rehabilitation, Spinal Cord Injury.**

I. Introduction

Paralysis, muscle weakness, and muscle impairment of the lower limb can cause difficulty in ambulation affected to many reasons, especially, resulting from neurological injuries, such as spinal cord injury and stroke, and the degenerative changes of the body structure, such as disc herniation, spinal stenosis, and spondylolisthesis [1, 3]. The patients, who had spinal cord injury (SCI) at L3, cannot control their lower limb parts. They had to live with a wheelchair however the standard facility in many countries is not suitable for a wheelchair. The BART LAB Lower Limb Exoskeleton (BART LAB LL-EXO) [2] was introduced and developed for solving those problems.

The design of this work is adapted to match the nationality of Thai people such as a robot's model and walking behavior. The database is collected to fit with the target group in all tasks, walking, sitting, and turning. Spring and camshaft system is integrated into the robot structure to reduce the required energy by absorbing the body weight into spring potential energy and released by the cam design.

II. MATERIALS AND METHODS

A. Overview of the design

From the National statistical of Thailand, mobility impairment has become the first problem in aged 15-60 years and more than half are male. Hence in this work, the model is set for male users with 169-171 cm height and 70-71 kg weight [11] adding 1.5 safety factors.

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B. Motion experiment and data analysis

We collect the data of position from the 'Optitrack(R) s250e' camera capture motion system. Tracking markers are placed in the position trunk, hip, knee, ankle, heel, and metatarsal bone (toe), especially two sides of the legs are attached in a turning motion. GRFs and their positions are collected by 'MatScan(R)'. For walking, we decided to walk along the normal gait cycle. This motion can be divided into 3 parts: starting, walking, and stopping shown in Fig. 1.

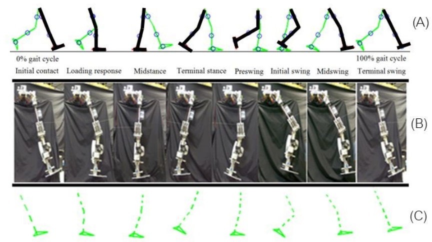

Fig. 1. Walking Experiment

In sit-stand and stand-sit motion, the patterns are similar. We do two different experiments, with arm support and without arm support shown if Fig. 2.

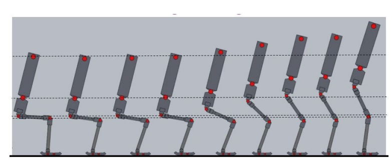

Fig. 2. Sit-to-Stand and Stand- to- Sit experiment

Turning motion is complicate, the scheme of turning is shownin the figure below. We divided one turning with 90 degree into 3 steps, thus one step compose of 30 degrees.

C. Energy Storage System

The chosen energy storage system is the spring system (Fig.3). Spring can store potential energy while it is compressed or extended according to the phase of the activity. The idea to absorb the energy in the gait cycle is approached. The system must store the energy from the toque that is produced by body weight. Then the energy from the spring that was stored in the previous phase should be released in the phase of high torque, for example, when the leg lifts the body. The advantages of this system are; that the system can absorb the torque produced by weight instead of joint, and the spring can help the motor to push the leg up in the cycle to reduce torque generating in both phases.

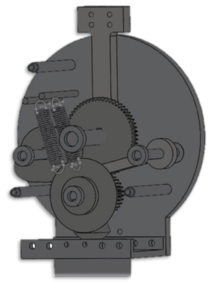

Fig. 3. Spring system used in knee and hip joint

The trend of the graph of knee and hip angle and torque is considered to find which motions are required torque or produced torque. The identical angles do not give a similar value of torque. It also depends on the direction of motion, the pose of other joints, and the position of COG of the body. To design the cam to use in the energy reduction system, the consideration of angle and torquing of each joint are necessary. At, the hip leg is swung like a pendulum, the torque requirement is increased when the leg is swung up and the torque is stored when the leg swings down by gravity. Like the hip joint, the knee joint has a phase of high torque requirement and energy storage.

D. Structural Design

The Mechanical design of this new lower limb exoskeleton robot is aim to have a light, active and agile structure. As we mention in the overall design section, the robot has a total of 11 degrees of freedom; 5 passive joints in the middle robot and other 4 joints at the ankle, and 6 active joints at the hip and knee. The middle joint of the hip allows the legs to move in a coronal plane or abduction and adduction. This joint is a passive joint because in a walk cycle moving in the sagittal plane is the most important and the movement in the other plane is supported by balancing the body while walking. Therefore, this joint is supposed to be a passive joint, and the movement depends on the pose of the patient.

There are two degrees of freedom at the hip in each leg; rotation and flexion/extension. For rotation, we use the motor directly to control the turning of the legs. This joint is primary use in the turning process. The motor is placed vertically to rotate the leg without transferring the power so the motor that uses should fit the torque requirement.

For the movement in the sagittal plane, the hip requires an angle of -20 degrees to 30 degrees from the normal alignment in walking but requires 90 degrees in sitting. Therefore, the total angle range of the hip is -20 degrees to 90 degrees. The looks of this joint are designed in a cylindrical shape. The main structure is divided into two parts; the inside plate and the outside plate. Shafts are laid across these two parts. The power origin is from the motor attached under the joint. The motor shaft is put into the cover and transferred to the bevel gear to change the orientation of the movement. Knee joint movement is primarily in the sagittal plane so we use only one degree of freedom in the knee joint. The range of angle of the knee, while walking is from 0 degrees to 50 degrees but for sitting, is extended to 90 degrees. Knee joints are designed to have the same looks as hip joints and also the components inside. The working system of knee joints is almost similar to the hip joint. The difference between these two joints is only in the cam for the energy storage system shown in Fig 3.

There are two passive joints at the ankle; dorsiflexion/plantar flexion and inversion/eversion. In the walk cycle, the ankle joint is required the highest torque but why does this design use the only passive joint. The torque that soars at the ankle joint is in the phase terminal stance with the dorsiflexion pose of the ankle. In this pose, the body is in front of the joint, and the torque in this phase is produced by the body weight, and the ankle joint tries to resist the weight. But to make the robot smaller and lighter we decide to cut the motor off from this joint and use the structure to absorb the torque produced by the body weight shown in Fig. 4.

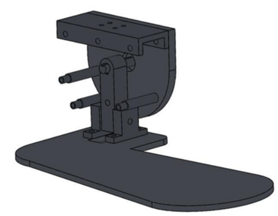

Fig. 4. Ankle joint

III. DISCUSSION

From the experiments, we collected the position and time in each marker and ground reaction force to explain the characteristics of each joint. The maximum torque appears at the knee when the knee joints absorb the body weight and the other peaks occur while the legs try to push off. For turning angle of each joint is explained in the term of relative angle. Applying the spring system equation to the maximum moment that occurs in each joint during all the experiments.

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