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Design and Implementation of a New Motorized-Mechanical Exoskeleton Based on CGA Patternized Control

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Abstract—**Exoskeleton is an active external mechanical structure attached to a part of human body to augment power or increase mobility of that body part. The exoskeleton is frequently used in military or rehabilitation purposes. In this study, we are focusing on the design and development of a novel mechanical design of the extremity lower-limb exoskeleton for the patients with spinal cord injury. The design is based on our lower-limb biomechanical analysis which a new concept of using a spring system for energy storage is employed in the designed exoskeleton to compensate the peak torques required at each joint. Our exoskeleton is consisting of 9 degree-of-freedoms covering the hip, knees and ankles. The introduced control algorithm for the exoskeleton is called "Patternized Control Approach," based on the Clinical Gait Analysis (CGA). A set of demonstrating results is shown, and is able to conclude a satisfactory performance of the system.**

Keywords—Assistive technology, lower extremity exoskeleton, paraplegia, exoskeleton, robots.

I. INTRODUCTION

EXOSKELETON is an active mechanical device attached to the part of human's body which is to augment or extend the performance of that specific or related body parts. In leg pathological patients, the lower-limb exoskeleton is also used to increase their mobilities.

A. Motivation/Background

In 2007, the disable persons have been increased to 1.87 million over the 67 millions of population recorded by Thai National Statistical Office [1]. More than 10 percent of the Thai disable persons have spinal cord injury, which are unable to control their lower part of body. Those spinal cord injured persons always stay in the same posture, or normally use wheelchair for their movements. Lacking of mobility for a long time can contribute medical complications, such as, pressure sore, atrophy, joint stiffness and thrombosis. Moreover, psychological problem can be occurred in the same group of patients. To relieve the symptoms, several procedures of physical therapy for rehabilitation have been treated to the patients.

The progression of science and technology is presenting the robotic exoskeleton to be an alternate rehabilitation device, which also increases the patient's mobility [2-4].

In this research, a novel mechanical design of a robotic lower extremity exoskeleton is introduced. The designed exoskeleton is to assist gait deficiency in paraplegic patients. Paraplegia is a type of spinal cord injury which the lumbar spinal nerve 3 (L3) or below is injured as shown in Fig 1. The designed exoskeleton consists of 4 degrees of freedom (DOF) in each leg (two of which are powered by electrical actuators) and 1 degree of freedom at the torso. The exoskeleton can perform flexion/extension at the hip, knee and ankle joints; abduction/adduction at the hip joint; and inversion/eversion at the ankle joint. The main locomotion of the exoskeleton is in sagittal plane using patternized control based on Clinical Gait Analysis (CGA).

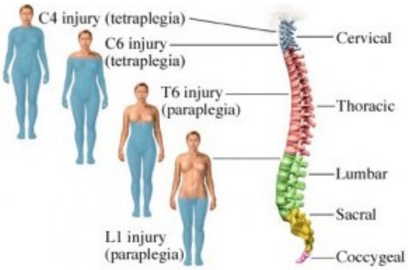

Figure 1. Level of spinal cord injuries
(Courtesy, http://stemcelltreatments.org)

B. Related Works

Several exoskeleton systems have been presented and successfully demonstrated in various purposes, worldwide. The exoskeletons can be divided into two groups which are performance-augmenting exoskeletons and active orthoses exoskeleton. (1) *performance-augmenting exoskeleton*: In late 1960s, General Electric was presented the Hardiman, the first full-body power assist system [5]. Kanagawa Institute of Technology, Japan developed a Nurse-Assisting Exoskeleton for assisted patient transferring [6]. Yagn's passive exoskeleton was presented in U.S. Patents in 1890 [7]. In 2002, Hybrid Assistive Leg (HAL) was developed and demonstrated by Yoshiyuki Sankai from Tsukuba University in Japan for both performance-augmenting and rehabilitation [8, 9]. In 2004, Kazerooni and his team from UC Berkeley developed BLEEX exoskeleton for military purpose [10]. A quasi-passive exoskeleton from MIT was designed to augment load-carrying capabilities during walking [11]. (2) *Active orthoses exoskeleton*: In late 1960s

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to 1970s Miomer Vukobratovic developed several versions of exoskeletons for helping paraplegic patients to walk [12, 13]. In 2006, the exoskeleton for patients and the elderly persons was presented by Sogang University (EXPOS) in Korea [14]. Robotics and Multibody Mechanics Research group from Vrije University, Belgium developed an exoskeleton powered by pleated pneumatic artificial muscles (a series of two single-acting pneumatic actuators). The main purpose of this exoskeleton was developed for gait rehabilitation [15]. The Institute for Biomedical Technology (BMTI), University of Twente, Netherlands developed the exoskeleton, called "LOPES" [16]. LOPES was also developed for rehabilitation purposed.

In the following sections, the paper is started with a study on human gait analysis and biomechanics of joints. Then, the conceptual design, prototype development and control algorithm are described. Preliminary demonstration and conclusion are then discussed.

II. HUMAN GAIT ANALYSIS AND BIOMECHANICS OF JOINTS

A gait analysis is studied on the pattern of human movement in both normal and abnormal gaits. The analysis is focused on a one-gait cycle. The gait cycle is represented as the walking-time interval occurring from heel-strike to heel-strike at the same leg. One gait cycle can be divided into two phases which are the stance phase and swing phase as shown in Fig. 2.

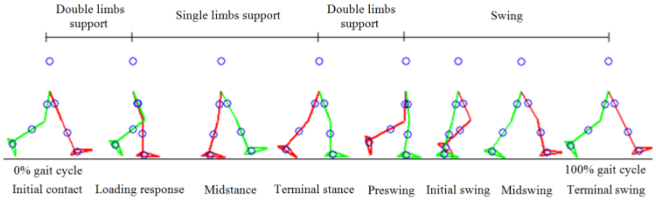


Figure 2. Eight postures of lower limbs in one gait cycle. Circles represent center of mass of body segment, thigh segment, shank segment, and foot segment (Top down)

In this project, gait analysis focuses on sagittal plane only. To analyze the human gait, this calculation assumes positive angles of hip, knee and ankle joint as counterclockwise as shown in Fig. 3. The angle of hip joint is measured by the deviation between the distal end and proximal end of thigh. The angle of knee joint is measured similarly as hip joint but using the deviation of shank instead. The angle of ankle joint is measured by the deviation between foot and shank.

The range of motions at hip, knee and ankle joint while people walk in normal speed are shown in Fig. 4.

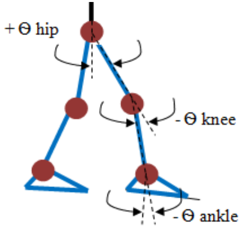
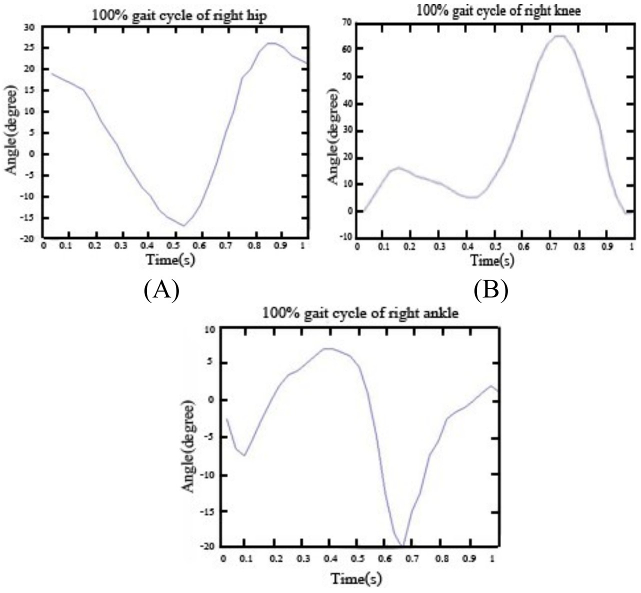


Figure 3. The angle of hip, knee and ankle joint, the positive joint angle is counter clockwise

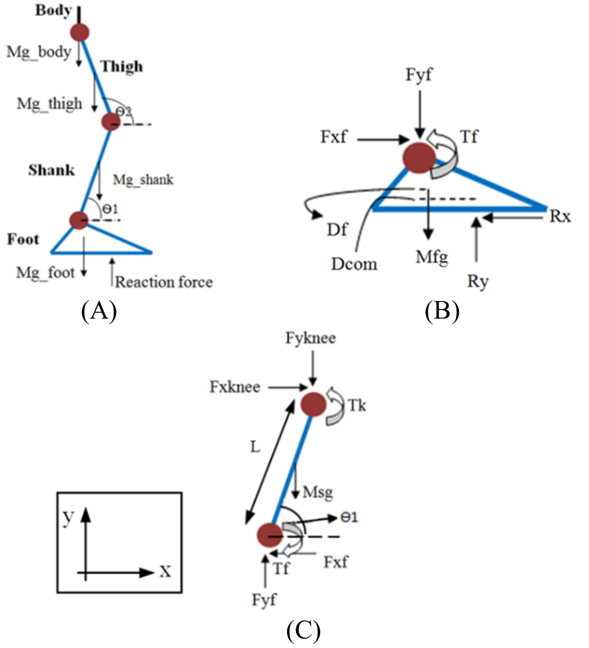


(A) (B)

(C)

Figure 4: The range of motion (angle in degree) in one gait cycle of hip (A), knee (B), and ankle (C)

In this part, the joint angle data are used to determine torque at the knee and ankle joint by using Static Analysis. Fig. 5 shows free body diagram of the whole leg, a foot and a thigh.



(A) (B)

(C)

Figure 5. Free body diagram of the whole leg (A), foot (B) and thigh (C)

To determine joint torque, the calculation assumes

1. People walk by upper body part line in vertical.
2. Upper body part is rectangle shape so the center of mass is at center of rectangle.
3. Ground reaction force at foot is linear. (The reaction force starts at heel when people is in initial contact position and end at toe when terminal stance position.)

Based on Static calculation, the reaction force (N) is equal to the whole weight as shown in (1), where Mg_{Body}, Mg_{thigh},

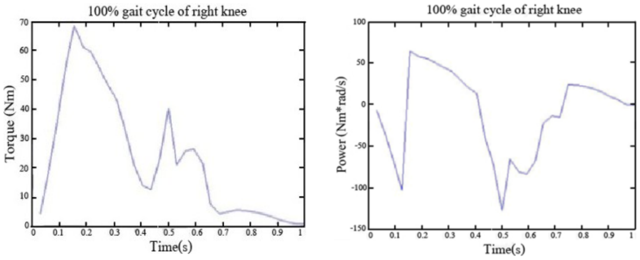
Mg_{shank} (M_{sg}) and Mg_{foot} (M_{fg}) are the weights of body, thigh, shank and foot, respectively. R_y is the reaction force at the foot in Y-axis. D_f is the length between the foot's center of mass and the ankle joint's center in X-axis. D_{com} is also the length between the reaction point and ankle joint's center in X-axis. F_{yf} is a force that applies at the ankle joint in Y-axis. L is a shank's length. T_f and T_k are torques at ankle and knee.

$$Mg_{Body} + Mg_{thigh} + Mg_{shank} + Mg_{foot} = N \tag{1}$$

$$T_f = \left(-R_y D_{com}\right) + \left(M_{fg} D_f\right) \tag{2}$$

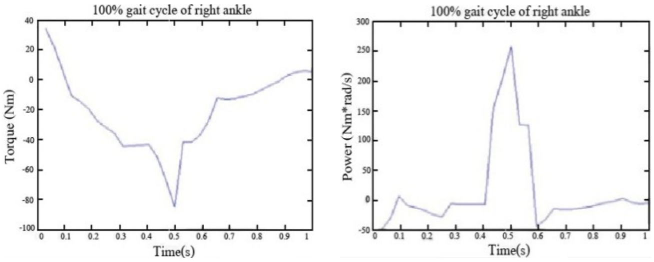
$$T_k = T_f + \left(F_{yf} \times L\cos\theta_1\right) - \left(M_{sg}\frac{L}{2}\cos\theta_1\right) \tag{3}$$

Torque and power at knee and ankle joint are calculated by (2) and (3), shown in Fig. 6 and Fig. 7. Maximum torque at knee and ankle joint are 68 and 85 Nm. In the meantime, Maximum power of each joint is 127 and 263 Watt.



(A) (B)

Figure 6. Torque (A) and power (B) at knee joint



(A) (B)

Figure 7. Torque (A) and power (B) at ankle joint

III. CONCEPTUAL DESIGN

This project is to develop a portable lower extremity exoskeleton for paraplegic patients who are injured at the lumbar spinal cord level three and below (patients are unable to walk by themselves). The exoskeleton's main motions are in the sagittal plane. Each leg consists of 4 DOFs and 1 DOF at the torso for both legs. There are 2 DOFs at hip joint for hip flexion/extension and hip adduction/abduction, 1 DOF for knee flexion/extension and 2 DOFs for ankle dorsiflexion and ankle eversion/inversion. Electrical motors are selected for actuating the exoskeleton at the knee and ankle joint (dorsiflexion). The conceptual design of the exoskeleton is shown in Fig. 8.

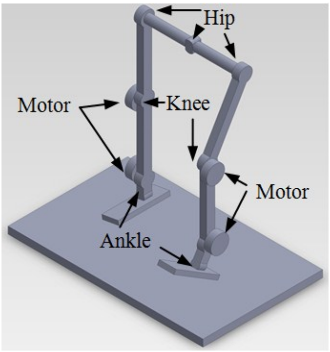


Figure 8. Conceptual design

IV. MECHANICAL SYSTEM

Spring is considered to be a mechanical device which is able to store and release energy. From clinical gait analysis, the torque and power at joints are very high. If only electrical motors would be employed to drive the knee and ankle joint, the required motor will be very large in sizes. This problem will also make the structure to be too big and heavy. The exoskeleton mechanism is applied spring compounds to work in collaborate with electrical motors to absorb the energy in the stance phase and release the energy in the midstance phase in human walking gait. With this mechanism, the motor size can be reduced tremendously. There are 2 tension springs at knee joints, absorbing energy in stance phase. Fig. 9 shows the torque requirement at knee joint when the exoskeleton is actuated with and without the spring system (red line and blue dash line, respectively). With this mechanism, the peak torque requirement for motor is reduced significantly from 68 to 33 Nm.

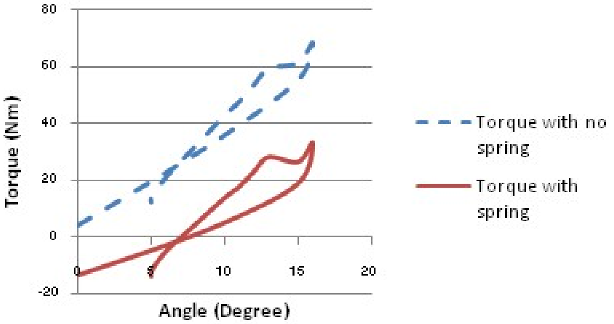


Figure 9. Torque requirement at knee joint

At ankle joint, two-linear-springs mechanism is used for the motions in sagittal plane. The spring system is designed to function in stance phase which the peak torque is occurred in this phase. The first spring is a linear compression spring which is located in front of the shank. One side attaches with shank and another side attach to foot. The second is a linear tension spring which is located in back of shank, and the both sides of spring are attached to the shank and the foot same as compression spring. Fig. 10 shows torque requirement at ankle joint when the exoskeleton is actuated with and without the spring system (red line and blue dash line, respectively). With this system, the torque requirements from actuators are significantly reduced from 52 to 9 Nm.

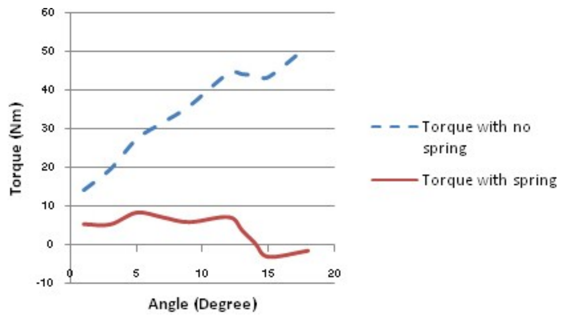


Figure 10. Torque requirement at ankle joint

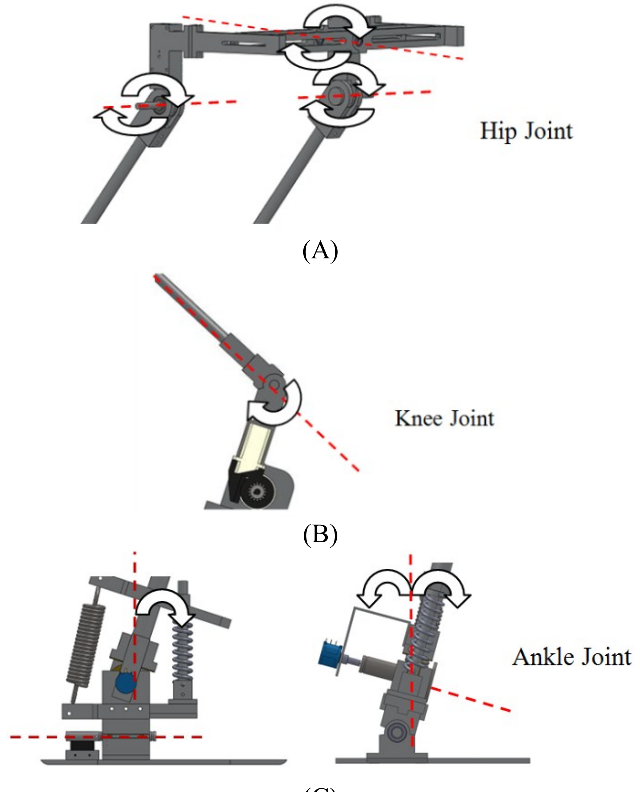
V. STRUCTURE AND DEVELOPMENT

This part discusses the range of motion for each joint, conceptual design of exoskeleton and torque requirement at knee and ankle joint. In this part, structural design and control architecture are described.

A. Structural Design

Hip joint in the exoskeleton is consisted of 2 DOFs (hip flexion/extension and hip abduction/adduction). The first DOF represents the joint for hip flexion (limited at 60 degrees) and extension (limited at -60 degrees) which is passed through the human hip joint and move in sagittal plane. The second DOF represents the joint for hip adduction and abduction in both legs. This joint is chosen to be a revolute joint about a single axis behind a patient and move in coronal plane for more natural walking and body balancing. Hip joints are shown in Fig. 11(A). Knee joint are the pure revolute joints, moving in the sagittal plane. The knee joint are designed for knee flexion and extension, limited at 0-65 degrees. In the knee joint, the range of motion is limited by our designed mechanical locking structures. The knee joint is shown in Fig. 11(B). The last one is the ankle joint. The ankle joint is composed of 2 DOFs, ankle dorsiflexion and ankle eversion/inversion. Both joints pass through the human joint. The ankle dorsiflexion joint is limited at ±18 degrees and ankle inversion/eversion is limited at ±15 degrees for each posture. The ankle joint is shown in Fig.11(C).

A lengthened bar is designed to lengthen behind the human torso to support the weight of power supply (battery set), controller board, and 2 motors for knee joints. At the left hand side of the knee's motor, a potentiometer of knee joint angle counting is setup to measure the knee angle. Hip joint, passed through the human hip, is designed as a passive hint joint. The pulley and gear sets are attached at this joint to transmit motor power to the knee joint. Potentiometer is mounted at hip joint to measure the hip's angle as shown in Fig. 12(A). The knee joint is designed as a pure hint joint attached with a pulley set and two tension springs in a specific box. Spring box mechanism is designed to store and release the energy at the 0-16 degrees to reduce torque requirement from the motor in the stance phase as shown in Fig. 12(B). The ankle joint is consisted of compression and tension springs, and the ankle's motor as shown in Fig. 12(C).

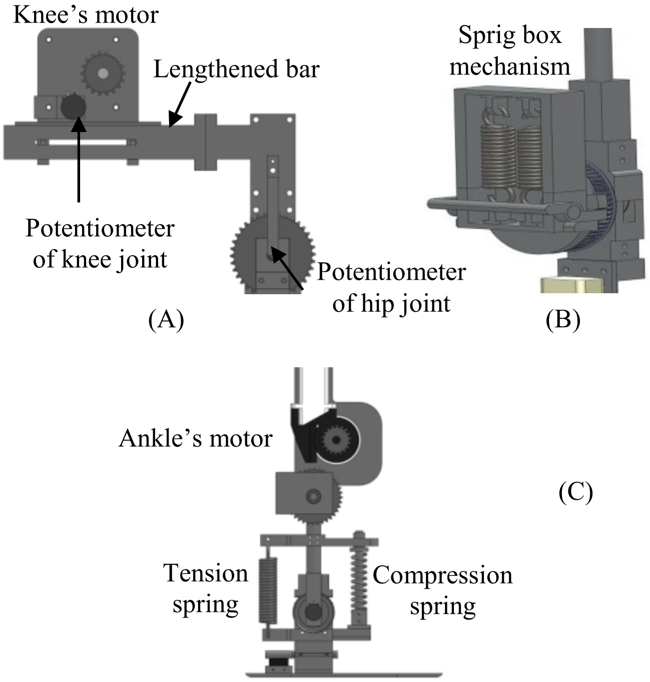


(A)

(B)

(C)

Figure 11. Design of range of motion of hip joint (A), knee joint (B) and Ankle joint (C)



(A)

(B)

(C)

Figure 12. Hip structure design (A), Spring box design (B) and Ankle joint design (C)

Potentiometer in ankle joint is mounted next to the pulley to measure the angle at the ankle joint. Thigh and shank parts are used for structural support and to connect the joints together. Both thigh and shank are designed to fit with a 170-cm height and 60-kg weight person.

B. Control Architecture

In this study, the exoskeleton's control system is implemented with the patternized control based on clinical gait analysis (CGA) of abled body. The control system is consisted of a micro controller, 4 motor control units and 6 measurement units (potentiometers). Arduino Mega 2560 is employed as the micro controller unit, which is pre-installed a human gait pattern, and receives the hip, knee and ankle joint's angles from the measurement units. With the gait pattern and joint angles, Arduino determines the new joint angles of knee and ankle for the next iteration to command the motor control units with the pulse width modulation method (PWM). The system employed a gait pattern from Dr. David A. Winter's study [17]. The control architecture of the exoskeleton is shown in Fig. 13. The computed angles are to be compared the knee and ankle joint angle from potentiometers. Until the difference of angles is in the range of ±1 degree, the motor will not operate.

Finally, the new motorized-mechanical exoskeleton based on CGA patternized control is assembled (See Fig. 14.)

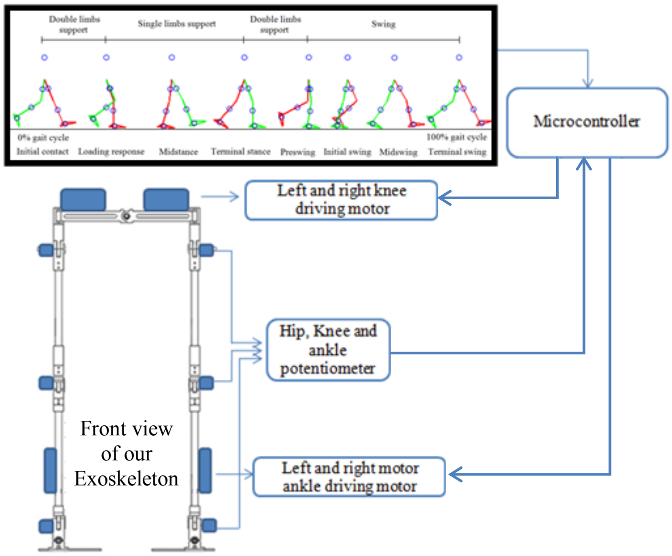


Figure 13: Control architecture

VI. PRELIMINARY DEMONSTRATION

The first preliminary demonstration focuses on the mobility checking on the designed exoskeleton. During the test, the exoskeleton is setup for the test by hanging the exoskeleton above the ground and applied external force at hip joint. The results show the full capability of the mechanism which is provided the full range of motions, and functions of the special spring system, operated at the respected time. For the control algorithm testing, the demonstration is setup as the mobility testing. D.A. Winter gait pattern (red line) and the simulation of gait pattern using MATLAB (green dash line) to simulate by the measuring angles from potentiometers, shown in Fig. 15 (A) and (C). In Fig. 15 (B) shows eight postures of the exoskeleton gait cycle.

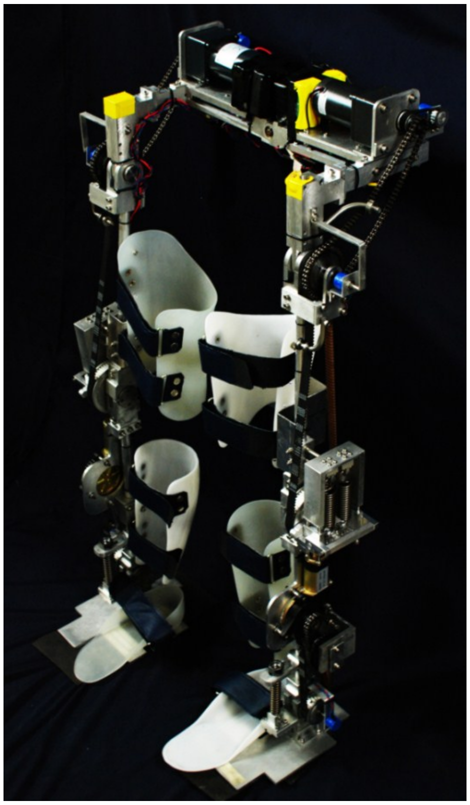


Figure 14. The new motorized-mechanical exoskeleton

Comparing with each gait cycle posture, the gait pattern by D.A. Winter and the gait pattern from potentiometer are almost the same posture except at the pre-swing phase. In comparison between exoskeleton postures and shapes in each posture are still showing some error due to the backlash problem, occurred from the tensile force in pulley's belt and gear's chain.

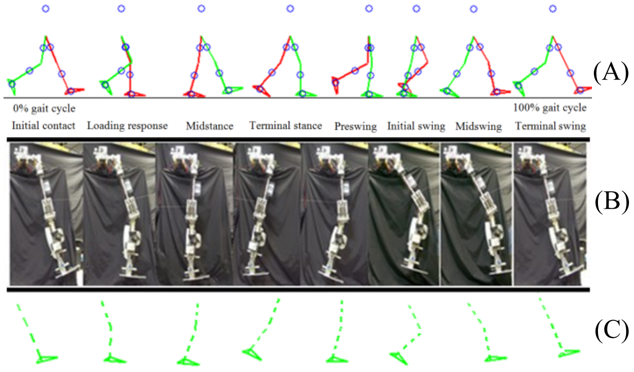


Figure 15. Simulation of eight postures of the exact gait cycle of Winter D.A. (A), the exoskeleton postures (B) and simulated gait cycle by MATLAB (C)

In the final step of preliminary demonstration, the exoskeleton is warned by the first author to demonstrate the operation as shown in Fig. 16. The result of the exoskeleton mobility presents the most likely gait pattern as D.A. Winter's human gait pattern. However, the response time of the control system is not yet satisfied for the regular normal gait cycle.

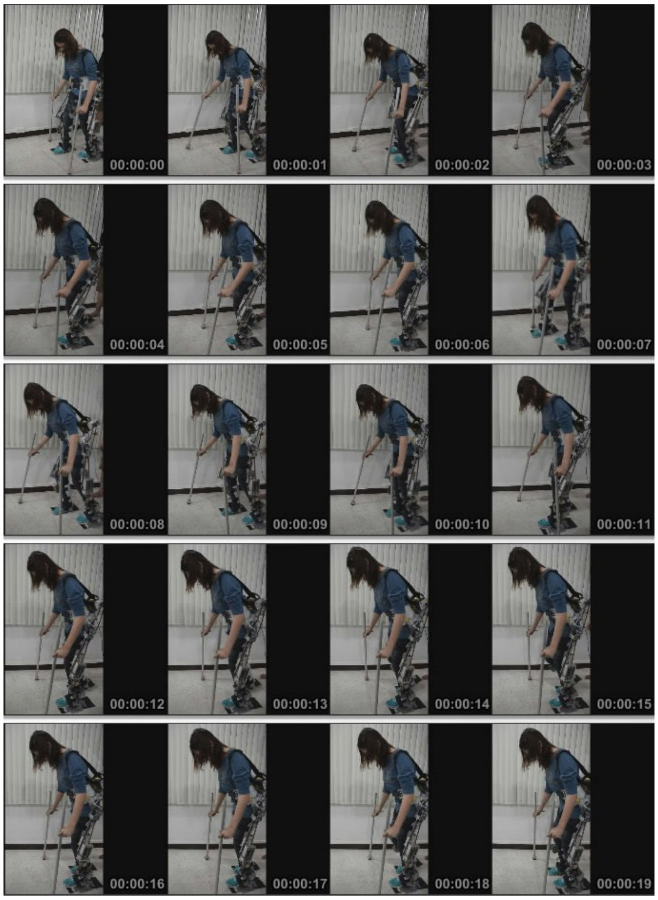


Figure 16. The demonstration of the new motorized-mechanical exoskeleton based on CGA patternized control

VII. CONCLUSION AND DISCUSSION

This study is to design and develop a new robotic exoskeleton with a control algorithm bases on the Clinical Gait Analysis (CGA). A designed spring-mechanical system is introduced to compensate the peak-torque requirements from the system's electrical actuators. Each leg of the exoskeleton consists of 4 DOFs at hip, knee and ankle, and 1 DOF at the connecting joint between both legs at torso of the patient. The detailed information on design, development and control have been discussed. The demonstration and its results show that the exoskeleton is able to perform assisting the walking steps by the pattern of gait cycle. The system's respond time, can be improved in comparable to the normal gait cycle and more complicated control algorithm.

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