A Novel 3-DOF HIP Exoskeleton for Kinematically Establishing Animal Model of Avascular Necrosis of the Femoral Head

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***Abstract*—This paper outlines a detailed description of the design on a 3-DOF hip robotic device for kinematically establishing animal model of avascular necrosis (AVN) of the femoral head. In order to realize the hip extension/flexion and abduction/adduction movements of rabbit subjects, a novel 2-DOF hip motion apparatus based on a pair of cardan joints is investigated. 2 electric grounded motors are used to drive rabbits passively in terms of predefined trajectories repeatedly with an additional periodical impact loading on the femoral head during motions. It is ideal to simulate usual forceful and repeated actions in sports, such as gymnastics and acrobatics, and initiated a new way to establish animal femoral head AVN models by means of kinematically simulating the real motion procedure rather than traditional medical or physiological operation method. With sets of experiments, the characterization of the exoskeleton system is discussed.**

***Keywords*—AVN, femoral head, kinematic animal model, exoskeleton, impact loading**

I. INTRODUCTION

Avascular necrosis (AVN) is a relatively common disease in which there is death of the cellular elements of bone or marrow, which usually leads to destruction of the hip joint and increasing musculoskeletal morbidity. The femoral heads are the most commonly affected sites for clinically significant AVN. It becomes a significant problem in healthcare because it often affects young adults and so common in sportsman, primarily gymnast. Different risk factors have been discussed, yet its etiology and the pathogenesis are still uncertain by the lack of a suitable experimental model [1][2]. To discover the chain of events resulting in osteocytic death, be it by necrosis or apoptosis, experimental models ought to replicate a “circulatory-deprivation” mishap, implicit in the practice among physicians of applying the epithet “avascular” to the disease [3].

Rodents are frequently used in preclinical tests of novel therapeutic modalities. Nishino et al. established a new model of femoral head AVN by dislocating the hip joint and ligating the medial and lateral circumflex femoral arteries and veins [4]. In the work of Peskin [5], an animal model for the study of necrosis of the cartilaginous and osseous compartments of the femoral head is developed by means of disrupting the blood circulation of rat’s femoral heads by incising the periosteum at the base of the femoral neck and cutting the ligamentum teres. Lehner and his co-workers have succeeded in producing an experimental animal model of DON, a form of aseptic bone necrosis, and have reported many papers regarding experimentally induced DON in sheep [6]. Mont et al. successfully used the trapdoor procedure with autogenous cortical and cancellous bone grafting for the early disease [7][8]. Frozen by liquid nitrogen is another popular method to study the animal model of the femoral head AVN, by which Takaoka produced the animal model in dogs [10]. A robotic device for studying rodent locomotion after Spinal cord injury was developed by Nessler [13][14]. This important work inspired the concept of a new way for animal model establishment by means of simulating the real motion procedure rather than traditional medical or physiological operation method.

The purpose of this study is to propose a novel 3-DOF exoskeleton apparatus that provides repeated extension/flexion and adduction/abduction motions with periodical impact on femoral head of rabbit hip for a long term to simulate the forceful and repeated actions as those frequently occurring in gymnastics. It has an insight to kinematically establish the animal model with qualifying effects of therapeutic interventions on the course of osteonecrosis of the femoral head, and pave a new way for analyzing the relationship between the gymnastics-like forceful and repeated actions and the femoral head AVN so as to prevent or reduce its occurrence.

II. SYSTEM MECHANICAL STRUCTURE

As mentioned above, the problems of establishing an ideal animal model of the femoral head AVN are mainly circumvented with the incorporation of two design features. The first key feature is to vividly reproduce the gymnastics-like repeated and forceful motions, which requires an elegant device with two grounded electric motors to realize 2-DOF motion simultaneously, namely extension/flexion and adduction/abduction. This feature is required to be firm and lightweight, and allows as low inertia as possible. The second of these features is an embodied impact trigger that can generate an adjustable impact load during action to mimic motions causing impact on the femoral head, such as the forceful landing in gymnastics.

The concept of exoskeleton devices, applying for human power augmentation and rehabilitation, inspires the orientation of the apparatus. Because of their unique limb-kinematics-anatomy based design principle, they are ideal equipments for repeatedly driving the subjects for a long term and an additional impact device is easy to be mounted onto its frame. A picture of the engineering prototype, along with the rabbit fixed shelf, is shown in Figure1. This drawing provides an overview of the main components of the system.

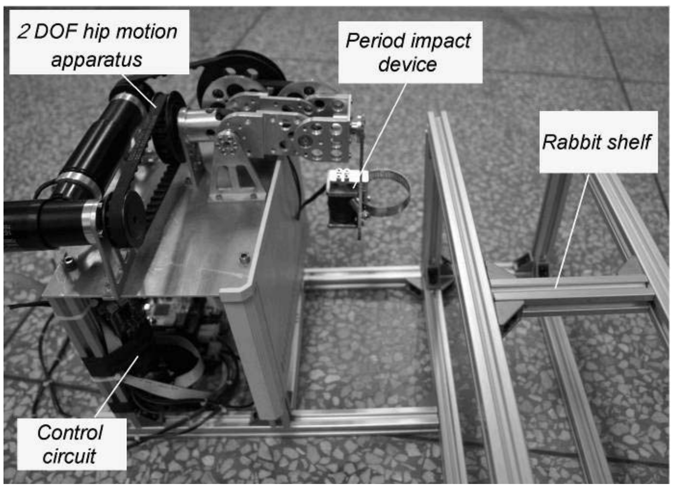


Figure 1. Overview of the system

A. 2-DOF hip motion apparatus

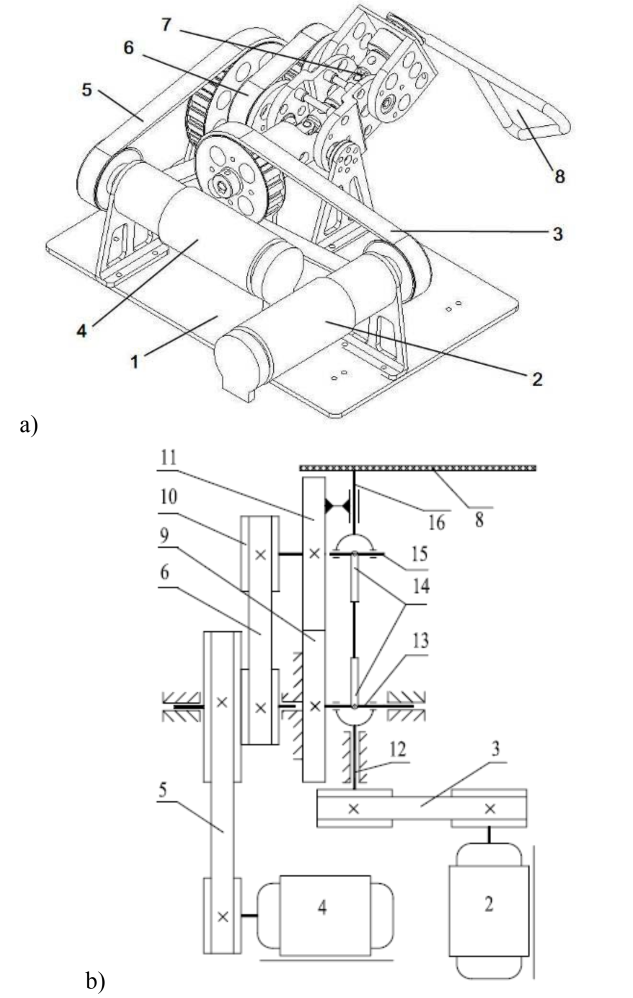
The prototype of 2-DOF hip motion apparatus is designed to provide repeated extension/flexion and adduction/abduction movements of rabbit hip, as shown in Figure 2.

The prototype consists of three main parts, including a pair of driving motors, a main flexible shaft for hip extension/ flexion, and a set of transmission mechanism for hip abduction/ adduction movement. The basic principle of the system can be explained as following:

1) Apparently the motion of the motor 2 can be fluently transmitted to the frame 8 via the tooth belt transmission 3 and the flexible shaft 7. The hip extension/flexion motion can be realized easily with the pendulum motion of frame 8.

2) Through the tooth belt transmission 5 and 6, the rotation of motor 4 can be translated into the rotation of gear 11, moving around the fixed gear 9, which composes a planetary gear mechanism. This motion drives the cardan joints pair 14 to rotate about axis 13 and frame 8 to rotate about axis 15, which well synthesizes the motion of adduction/ abduction.

3) In order to ensure the motion of frame 8, namely the angular position, velocity and acceleration, as the same as those of the motor 2, a pair of cardan joints is adopted, and also the planetary gear mechanism composed by the fixed gear 9 and gear 11 always promises $\alpha_1 = \alpha_2$, as shown in Figure.3.



1-panel; 2-motor for extension/flexion motion; 3-tooth belt transmission; 4-motor for abduction/adduction motion; 5-tooth belt transmission; 6-mechanism for abduction/adduction; 7-flexible shaft for extension/flexion; 8-frame; 9-fixed gear; 10-output of part 6; 11-active gear; 12-input site of flexible shaft; 13-axis 1 of cardan joint pair; 14-cardan joint pair; 15-axis 2 of cardan joint pair; 16-output site of flexible shaft

Figure 2. a) Prototype of the 2-DOF hip motion apparatus; b) Planar kinematical schematic diagram.

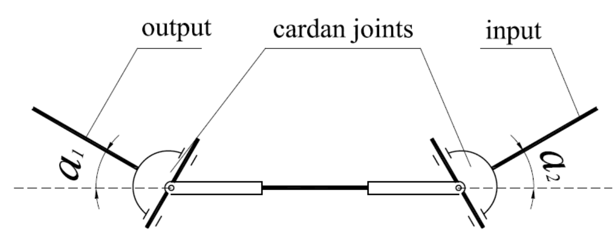


Figure 3. Operation principle of the cardan joints pair

B. Periodic impact device

For establishing a better animal model of the femoral head AVN, besides the repeated action, it also requires to bring impact on the hip of rabbits at a certain point during the motion for vividly simulating the forceful actions such as the sudden touchdown of gymnastic players. Usually this impact is equal to 10~15 times weight of the subject itself. This presents an engineering challenge. Here a solenoid based impacting device is introduced. This device is widely used to generate a large force instantly [11][12]. The solenoid pushes a steel rod while the straight kick brings rabbit thigh to hit its hip directly.

Figure 4 outlines the structure of the impact device. The rabbit leg is fastened on the frame with neoprene straps at its thigh and shank. Additionally, the rabbit thigh is attached to the spool by holding together both ends of a hoop. As a result, the impact generated by a push solenoid can crash on the femoral head of rabbit hip joint. Currently a push type solenoid is used. Its design parameters are optimally determined with the help of HFSS TM (Ansoft, USA), which is the industry-standard simulation software for high performance electronic design.

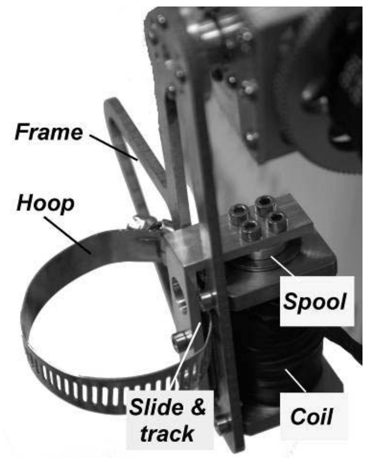


Figure 4. Structure of the impact device

The main idea in power elevation is to store energy in a capacitor with 5000μF, then discharge it when the solenoid is activated. The straight forward hit force is up to about 200N (about 10 times weight of the rabbit). Since the power of the straight forward hit can be adjusted from 0N up to about 200N, this is done by simply shortening the time the capacitor's voltage is induced into the solenoid. Because the capacitor charge level is very high, the device discharges it using a power MOSFET. A PWM signal generated by a micro control unit is sent to the MOSFET to control the flow of current through it and thus control the intensity of the impact.

III. CONTROL ARCHITECTURE

A. Hardware

The 2-DOF device with function of extension/flexion and adduction/abduction is driven via toothed belt by the DC motors (Maxon TM RE36, Interelectric AG, Switzerland). Encoders are mounted at both motors to measure the motion angles respectively. Therefore, an individual position close control loop has been implemented for each drive. CAN bus bridges the PC and small-sized full digital smart motor controllers (Maxon TM EPOS 24/5, Interelectric AG, Switzerland). The motion pattern and intended speed can be adjusted accordingly. Also the PC can set the desired impact force via RS232. A control board with ATMEL mega 128 MCU is designed to receive the command from PC and implement the closed-loop impact force control with a PWM signal. The architecture of the control system is illustrated in Figure 5.

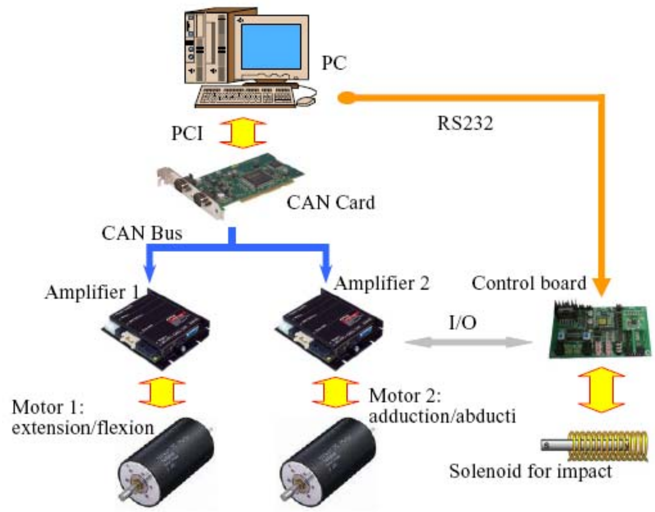


Figure 5. Control architecture of the system

B. Control mode

As it is not well known, either the repeated motion of hip or the powerful impact force, or their integration mainly causes the femoral head AVN. In the system, there are two available control modes. In the first mode, the motion of extension/ flexion and adduction/abduction and the impact force can be controlled independently. In the second mode, the impact force is periodically produced at a certain moment during hip motion as pre-programmed. As a result, with different control mode, the system can supply a specific comparison of the effect of each factor in kinematical model establishment.

C. Software interface and database

Since this device faces to researchers or physiotherapists, its user interface must be friendly and easy to operate LabVIEW TM is a fully featured programming language produced by National Instruments, USA. It is a graphical language quite unique in the method by which there is no text based code as such, but a diagrammatic view of how the data flows through the program. In contrast to text-based programming languages, where instructions determine program execution, LabVIEW uses dataflow programming, where the flow of data determines execution. We can write most of our "code" with only the mouse. If structured "properly", this "code" can pass as our flow chart.

Figure.6 illustrates the user interface programmed by LabVIEW. It includes the column of system configuration, motion parameter setting, operating panel and data real-time display. The operator can change the motion range, motion speed, motion duration at the user interface.

An additional important part of the user interface is the database. It is used to record the control mode and settings, as well as the experiment data. After each experiment, a detailed report is created to the user.

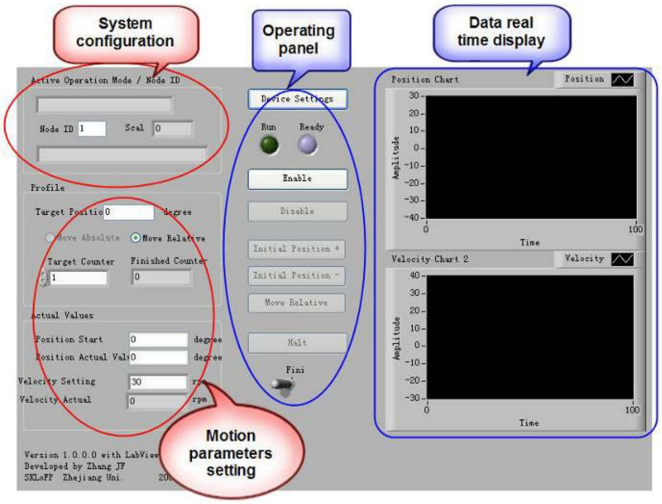


Figure 6. User interface programmed by LabVIEW

IV. EXPERIMENT DISCUSSIONS & FUTURE WORK

The goal of the present study is to determine the reliability and validity of the design of a 3-DOF exoskeleton device and its pioneer application in establishing an animal model of the femoral head AVN by repeated motion with a period impact pressed on femoral head. In the experiments, the rabbits were fixed on the shelf with leg fasten on the frame, and driven to move with the device 5 days per week for 4 weeks. For each experiment session, different motion range (-120° ~120° for extension/flexion and -60° ~60° for adduction/abduction), motion speed (0~5rpm) and impact force (0~200N) were tested.

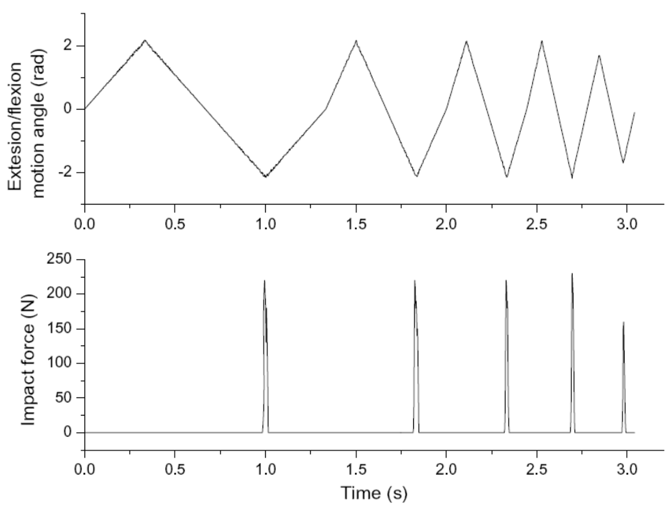


Figure 7. Average characterization of the system with sets of experiments

Figure 7 illustrates the average characterization of the exoskeleton device performance with sets of experiments. In the upper plot, the 1st period represents the average performance of the system at 1 rpm speed, and the 2nd for that at 2rpm speed, and up to 5rpm speed. When the rabbit hip moved to the -120° position with maximum extension, a corresponding impact was generated. The present results indicate that the system had solid performances at the motion speed up to 4rpm. Neither the performance of the 2 DOF hip motion apparatus nor that of the impact device was satisfying. The former was restricted by the motor up/down nature and the burden on the motor, especially the inertia of rabbit thigh and the friction from rabbit hip joint. If necessary, the current actuators can be replaced with larger power motors to cover this problem. Also the altitude of the impact dropped to about 160N when the system moved at 5rpm motion speed. It was mainly influenced by the non-completed charge of the capacitor due to limited charging time. Some improvements on the control circuit for charge will be put forward in the future. As a result, the existing system was advised to be utilized within 0~4rpm motion speed.

In addition, as evaluating the model of after a long term repeated forceful motion is a difficult task due to the complex nature of the etiology and the pathogenesis of the femoral head AVN, current assessments are relatively coarse. Future investigation will refine the use of this technique in animal model establishment with the kinematical method, and precise assessments will be defined.

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