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Powered Orthosis and Attachable Power-Assist Device with Hydraulic Bilateral Servo System

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Abstract— **This paper discusses the developments and control strategies of exoskeleton-type robot systems for the application of an upper limb powered orthosis and an attachable power-assist device for care-givers. Hydraulic Bilateral Servo System, which consist of a computer controlled motor, parallel connected hydraulic actuators, position sensors, and pressure sensors, are installed in the system to derive the joint motion of the exoskeleton arm. The types of hydraulic component structure and the control strategy are discussed in relation to the design philosophy and target joints motions.**

I. INTRODUCTION

The expectation to the rehabilitation robot from persons with sensory-motor disability is growing as researches are conducted to produce promising devices. Human exoskeleton or a wearable robot are emerging topic not just for the physically disabled, but also for the senior people with declining physical ability and workers in physically heavy labor which includes transferring heavy load in restricted space, e.g. caregivers. Just to name a few, researches on ARMin [1], Limpact [2] and other researches in reference [3]-[10] are exoskeleton system and actuators for upper limb therapy and assistive device which are milestone projects in the field. The novel technologies reported in these researches may be promising. However, the systems require appropriate functional design based on their application. Therapeutic robots' aim is to recover the lost or decreased function of the limb by providing repeated motion with the robot. Whereas, Assistive robots' aim to enhance the joint motion or torque to counter act gravitational force to compensate the weakness or paralysis of the upper limb. Power-assisting robots are similar to assistive robot on the functional target, however the user's ability is different since the assisting robot are limited in selecting the control signal source. Furthermore, exoskeleton robots are still under research and development, and require user evaluation as well as clinical trials to advance the system to be fully practical to extensive users. Since these systems target to substitute or retrain human muscular system, a comparable measure of these systems is the reproducibility of the human muscle characteristic. In this paper, our research and development of powered orthosis and power-assisting deveice from this perspective is discussed.

II. HYDRAULIC BILATERAL SERVO SYSTEM

As to meet the goal to develop a compact exoskeleton robot with an actuator simulating the human muscle, we set the following design feature to be achieved in our system to be a wearable and portable rehabilitation device for the user with limited function in the upper limb.

The first feature is the consistence of output power and safety in the design. The actuation mechanism needs to have sufficient power to maintain the joint position and drive the object load, including human body, while fulltime observation of abnormal loading during movement. The Second feature is to be capable of yielding to excessive and brunt force. Third feature is to maintain the holding object at electrical power shutoff while having the mechanical break off at emergency. Fourth feature is minimizing the energy source and total size and weight of the system to be portable. And the last and fifth feature is the user-friendly operation method or the input signal that does not require long-term and sophisticated training before use.

To meet the goal, we propose a hydraulic transmission mechanism resembling the human articular and muscular arrangements of the upper limb to develop a human exoskeleton robot. The transmission mechanism, Hydraulic Bilateral Servo System (HBSS) consists of master hydraulic actuator driven by an electromagnetic motor and a slave hydraulic actuator connected in parallel to the master actuator (See Figure 1) Silicon oil is encapsulated within the actuator chamber and tubing and balances the piston position based on the ambilateral hydraulic pressures on the piston. Potentiometers are attached to the master and slave pistons to instrument the piston displacement for feedback position control. The signals from the pressure sensors in the master-slave tubing are amplified and sampled utilizing two multiplexers connected to analog-to-digital converter ports on

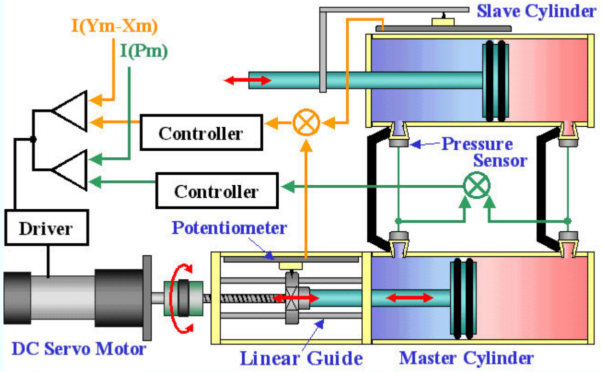

Figure 1. Fundamental model of HBSS Strucure with master cylinder and slave cylinder and the structure of mono-articular HBSA.

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the microprocessor. The microcomputer screens the varying signal from the pressure sensors for suitable pressure feedback control. Based on the control signal loop in the controller, the system can be designed to have position control, force (pressure) control, or hybrid control. Based on this basic structure, series of HBSS has been developed by selecting the slave hydraulic actuators from rotary hydraulic actuator and cylinders with regulating valves. Two mechanism resembling the upper limb anatomy, bi-articular Hydraulic Bilateral Servo Actuator (HBSA) and pronosupination HBSA are described in the following subchapters.

A. Bi-articular Hydraulic Bilateral Servo Actuator

Bi-articular HBSA is designed based on the design concept of mimicking the bi-articular and mono-aricular combined muscular structure while fully taking the advantage of the hydraulic characteristic of the HBSS. The bi-articular HBSA has two piston rods on the both end of the slave cylinder and three solenoid valves and pressure sensors embedded in the tubing regulate the flow of the hydraulic fluid (See Figure 2).

First, the antagonistic pairing muscles are interpreted in the design as the ambilateral pressure balance of the pistons. With the enclosed fluid in the HBSA, the Bernoulli's law and equation of continuity governs the dynamics of the piston output force and motion. Therefore, theoretically, when all valves are opened and master piston unlocked, the liquid flow within the parallel tubing of the master and slave cylinders works to generate complementary motion of the pistons. Furthermore, the antagonism functions as safety and power-saving feature since the arm posture is mechanically self-maintainable even without electrical power. Second, the mono- and bi-articular muscle functions are represented by the structure of the cylinder and dynamic switching control of the solenoid valves. A simple on/off control of the valve switches the joint to be driven and single-joint movement of the shoulder or the elbow can be selected. Furthermore by dynamically changing the open/close ratio the position of the slave piston rods can be driven simultaneously with a servo motor on the master cylinder.

B. Pronosupination Hydraulic Bilateral Servo Actuator

Pronosupination HBSA is designed by mimicking the radioulnar mechanism of the human forearm. The wrist rotaion in industrial robots are commonly a simple uniaxial joint, whereas, the rotational axis of the human forearm for pronation/supination movement is a gyrating axis with a positive taper angle in the proximal-to-distal direction from the longitudinal axis of the forearm. The skeletal structure of the radius gyrating around the ulna with the bone head of the radius tacked by the anular ligament enables this movement. With the intention of using this mechanism to twist the forearm, the contact points on the user’s forearm is required to rotate around the human joint without inducing abnormal pressure, shear force, or torsion torque to the arm.

To meet these design criteria, the radioulnar mechanical structure of the forearm is introduced in a bottom-up layout as shown in Figure 3. The geometric difference and output force difference generates the rotational angle and torque of the frame link connected to the oreclanon saddle, when expanding and contracting the two direct drive cylinders in the pronosupination HBSA. The bed plate, which the palm is resting on, is connected to the forearm base frame with a passive joint. This allows the palm to rotate with the forearm while the displacement of the palm center is minimal. This is an advantage for pre-posturing the hand in approaching the target object for grasp and manipulation. As for the control of the actuator, the output of the pronosupination is theoretically controllable in relation to the phase difference between the two cylinders. The structure of the cylinder layout and the antagonistic balance mechanically limits the motion range, maximum torque and speed of the pronosupination within critical boundaries.

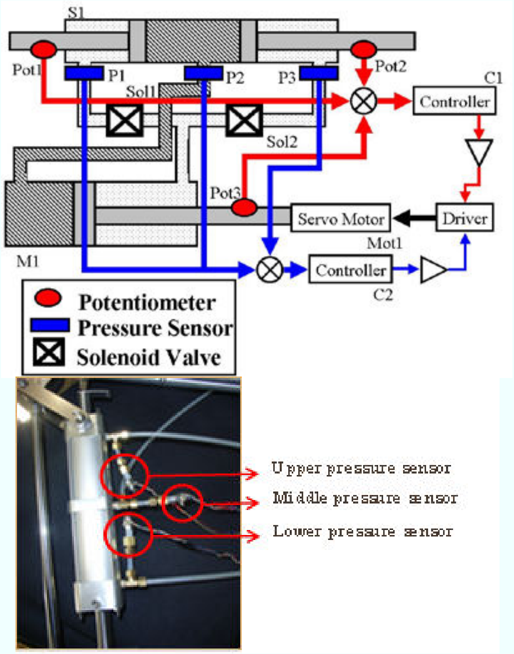

Figure 2. Bi-articular HBSA and the three pressure sensors with in the master-slave actuator tubing.

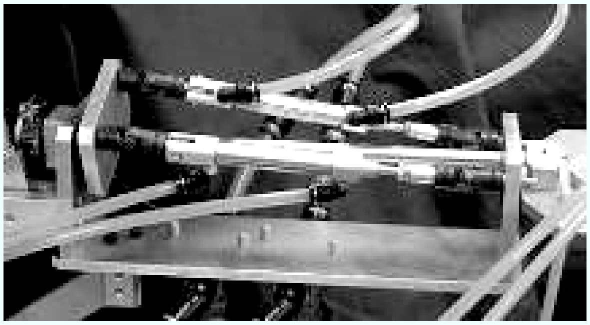

Figure 3. The prototype of the pronosupination HBSA

III. ATTACHABLE POWER-ASSIST DEVICE

The developed body carrying attachable power assist device is shown in Figure 4 and 5. The slave unit is a dual-arm human exoskeleton robot which is connected to the caregiver at the forearms. Six HBSS slave cylinders are mounted on one arm. The bi-articular HBSA is installed in the upper arm and rotary HBSA is installed to assist the wrist palmer flexion. Two mono-articular HBSA slave cylinders are installed to compose a universal joint at the height of care giver's hip. And a mono-articular cylinder is mounted at the height of ankle joint.

The target task of this device is to assist the caregiver to lift, carry, and lower the care recipient's body, weighting under 600 N, from height of 200 mm from the ground, e.g. a futon, up to approximately 800 mm, e.g. a high bed, in a comfortable way. The caregiver must have the freedom to approach, release and maintain close contact with the recipient's body. To meet this, the body posture of the care recipient's body is required to be arbitrarily-specified, whereas the position, especially the height, of the body at start and end of assistant can be constant in the robot's base coordinate system. Consequently, the wrist, elbow and lateral direction of the hip joint control is designed with the augmented motion control equivalent to the powered orthosis control strategy, and the shoulder, ankle and longitudinal direction of the hip joint is driven by replaying a preprogrammed trajectory in constant speed with a triggered start point at the motion phases. Figure 6 discribes the pressure sensor output of the middle pressure sensor on the bi-articular HBSA at open-loop positioning control of the arm end. Dead time and overshoot are seen and requires modifications. However, the pressure stabilizes to maintain the joint angle within a small oscillation when the motor stops. Since the forearm comes in contact with the bed clothing as well as the care recipient, the potentiometers are not installed on the slave cylinder. To structure the feedback loop for positioning, pressure sensor-based control with pressure difference between the bottom and rod side chambers are developed [15].

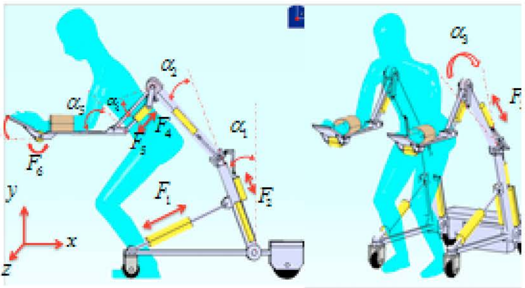

Figure 4. System diagram of the upper arm HBSA of the Rehabilitation Robotic Arm. The master unit (cylinder and motor) and controller are installed behind the backrest of a wheelchair.

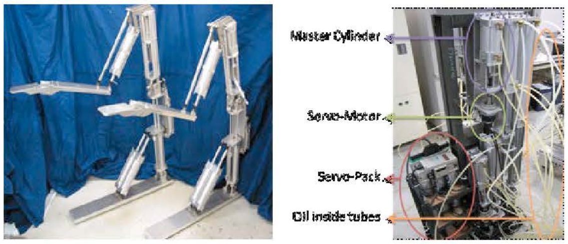

Figure 5. Body carrying attachable power assist device. Slave unit without the tubings (left) and Master unit (right). The dimensions of the master unit rack, including the 12 master cylinders and the Servopacks are 300 mm wide, 528 mm long, and 1370 mm high.

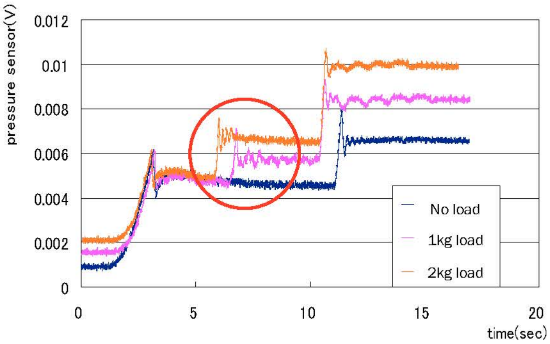

Figure 6. The middle pressure sensoroutput of the bi-articular HBSA's pressure sensor with and without initial load at arm end

IV. UPPER LIMB POWERED ORTHOSIS

The prototype exoskeleton arm of the upper limb powered orthosis is shown in Figure 7. The arm consists of links and joints with total of 7-DOF: 3-DOF shoulder, 1-DOF Elbow, 1-DOF forearm, and 2-DOF wrist. Four types of HBSA are mounted on the arm. Mono-articular HBSA, which is composed of a slave cylinder with single piston rod, is mounted on the shoulder for adduction/abduction. Rotary HBSA are mounted on the base frame on the wheelchair for shoulder lateral/medial rotation, and on the forearm for each wrist movement: palmar/dorsal flexion and radial/ulnar flexion. Bi-articular HBSA and Pronosupination HBSA are mounted on the upper arm for shoulder and elbow joint actuation, and on the forearm for pronation/supination, respectively. The motion of the Pronosupination HBSA is tested and the relation of the total output torque, cylinder output torques and the joint rotation angle is measured and plotted in Figure 8. The cylinders are activated with the phase difference of $\pi/2$. As seen, the maximum total output can be obtained at rotation angle of $\pi/4$

The upper limb powered orthosis is designed for assisting person with cervical spinal cord injury or muscular dystrophy symptoms, those with paralysis or weakness in upper limb movement. In the assistance mode, the arm is operated directly by the user wearing the orthosis. The small motions of the user's arm causes joint torque fluctuations of the orthotic arm, which are detected by the mounted pressure sensors in the tubing. When the system detects the variance exceeding the preset pressure changing threshold, the joint is driven at a constant speed in the direction of the force exerted, so the motion of the user is augmented while predictable. Consequently, the controller of the powered orthosis is intuitive and userfriendly.

V. DISCUSSION

HBSAs are developed to meet the design feature of a compact exoskeleton robot. However the forth feature is not fully satisfying, especially in the sense of portability. The slave unit of the HBSA enables a compact design of the human exoskeleton, however development and design modification and required in the master unit. The current structure with cylinder and lead screw transmission mechanism requires a long straight installation space which is not easy to secure on the human body surface. We are

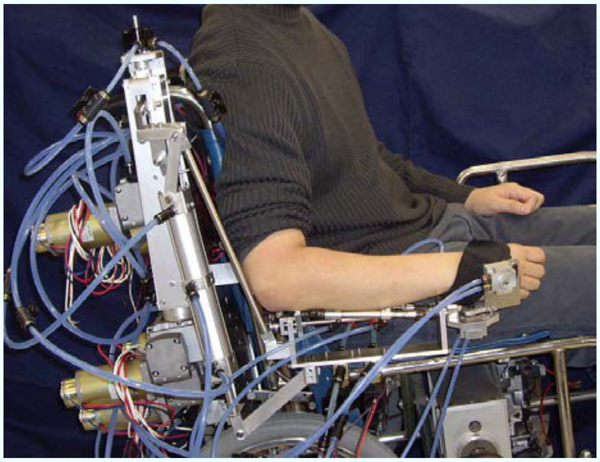

Figure 7. Hydraulic Bilateral Servo Ssytem Upper limb powered orthosis. The bi-articular HBSA is implemented in the upper arm and pronosupination HBSA is implemented in the forearm of the human exoskelteon robotic arm

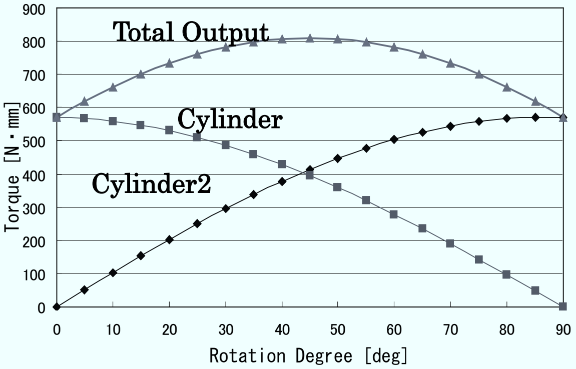

Figure 8. The relation of the total output torque, cylinder output torques and the joint rotation angles of the Pronosupination HBSA

currently testing the prototype master unit which is consisted of a bi-directionally rotatable internal gear pump. The technological development of the highly efficient pump mechanism in the artificial heart can be one solution to this problem, if the technology can be transfers while allowing bidirectional intermittent flow.

Originally, HBSS was developed under the design strategy of slow speed operation around 1Hz. Therefore, the antagonistic property between the piston pressures in the cylinder chambers promised high positioning accuracy in open loop control of the slave cylinder piton rod. Furthermore, the size of the cylinders used in the master and slave units was small. Current application and size of the cylinder has widened and large diameter master cylinders with unadjusted tube opening are being operated in non-stationary speed. Under such condition, control of the slave piton rod's speed and position requires identification of transient response based on dynamic characteristic of the system. Furthermore, feedback control of the joint motion will be tested by embedding hydraulic control valves and flowmeter in to the system to improve the coordinated joint motion control.

Finally, for clinical application, upper limb exoskeleton robot design needs new design strategies to improve the efficiency of donning/doffing the device, as well as comfort of wearing the device in longer terms. The time and trouble required to don/doff the device is crucial to continuation to use the device. Furthermore, more compact designs are required for home-use upper limb exoskeleton robot, especially for hemiplegia. Developing a device to invoke coordinated motion of the upper limb in daily life should distress the user and lower the barrier for social participation. Orthotic design targeting to compensate certain muscle should merit individual with paralysis of peripheral nerves. The knowledge of muscular anatomy and neurophysiology should lead to novel compact design of the device, and the therapeutic outcome found by using the device should fruit the study in neurorehabilitation.

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