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LOWER LIMB HUMAN MUSCLE ENHANCER

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ABSTRACT

This paper describes the design, control, and testing of a Human Muscle Enhancer (HME) system that will augment the muscle capabilities of subjects requiring partial lower-limb weight-bearing gait support. The HME described in this paper is a pneumatically actuated quick connecting exoskeleton system that attaches to the foot and hip area of the body, thus "closing" the lower body kinematic chain. Control of the system is achieved by using encoders at the knee joints and Myo-Pneumatic (MP) Sensors implanted into the shoes and outer garments of the human. To test this design concept, a lower body exoskeleton test fixture has been fabricated. The test fixture mimics the human leg with the top cylinder providing the body weight on the leg. Another cylinder acts as leg muscles to provide the adjustable human reaction of the leg. Preliminary open and closed loop control tests have been performed that demonstate the capability of controlling the HME using the MP sensors.

NOMENCLATURE

Human muscle enhancer, myo-pneumatic, exoskeleton, actuator.

INTRODUCTION

Human Muscle Enhancers (HME) have been proposed as a means to improve the physical performance of humans while performing a task or training. Such systems could be used in applications such as medical rehabilitation, sports training, in the heavy lifting industrial sector, in space activities and training of astronauts, and by military personnel while in combat or training. In this paper we present our studies and prototypes in the area of lower limb HME.

Our society has many patients with debilitating diseases or being in a rehabilitation phase [1] such as: a) *Rheumatoid arthritis,* a chronic inflammatory disease; b) *Osteoarthritis,* a progressive joint disorder; c) *Bursitis,* an inflammation of the lubricating sacs surrounding the joint capsule; d) *rehabilitation after reconstructive surgery* (hip replacement and knee prostheses; foot and ankle bone surgery); e) *rehabilitation after sports related injuries*. All these patients may need ambulatory aids to sit, to stand, and to walk. Depending on the ability of the patient, the aid can be a human helper with or without the assistance from passive aids such as a cane, crutches, or walker. The Human Muscle Enhancer (HME) can minimize the number of human helpers by providing partial support to the patient.

In the industrial and healthcare industry, many workers who lift heavy materials or equipment experience lower back injuries resulting in work time loss, workmen's compensation insurance premium increases, and diminished employee productivity. Patient transfer is strenuous to the human caregiver, causing serious sprains and strains of lower back, lost time from work, worker's compensation claims, and a financial burden on the health care industry [2]. With new

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advances in medicine, many individuals are living longer. With the rising senior population, health care costs are also increasing due to the increased assistance required by the elderly. The HME can help reduce this cost by providing an alternate option to a health care giver in situations were the elderly have control with partial weight-bearing gait.

In the military arena, personnel in the field will benefit if they have greater load carrying capability with less strain, and ability to ambulate further distances than present conditions allow.

The use of non-human power to enhance human muscles is not a new concept. In the 1960's General Electric Corporation designed and built "Hardyman"[3]. Hardyman was the first attempt at a man-amplifying "exoskeleton" operated by a human who wore it like an outer garment. The human controlled the outer exoskeleton by actuating inner exoskeleton hydraulic sensors, and providing a power amplification ratio of 25:1. Hardyman was expensive, bulky (weighing 680 Kg), unstable, and unsafe for the operator. "Pitman" [3] is a design concept from the Los Alamos National Laboratory for the Army. The human operator is fitted inside a fiberglass composite powered "Body Armor" that is driven by photo-reactive polymer-gel muscles. It is battery powered, weighs 230 Kg., and is capable of carrying a load of 135 Kg. "Jedi" [4] is another design concept that involves pneumatic actuators at each of the body joints. It requires a power unit that is pulled along by the human, and connects to the human operator by means of an umbilical cable, housing a set of power wires and tubes. The "Human Extender" [5] is a hydraulic robot manipulator that operates in direct contact with the operator and it is worn like a suit. The operator provides the intellect to manipulate delicate objects, avoiding obstacles, assemblying intricate objects, and having the ability to manipulate and modify activities on-the-fly. The extender, on the other hand, is able to provide the physical strength capability that the operator lacks, thus complementing the human. Its main use is in the industrial area for lifting heavy objects.

While the above designs are intended for heavy lifting, other designs have been geared towards assisting humans with physical disability. Patients with spinal cord injury (SCI) lose mobility that results from the paralysis of the lower limbs. Electrical stimulation of the motor nerves is used to restore limited mobility. As part of the rehabilitation regimen, the patient is required to stand and walk. This causes rapid muscle fatigue from the stimulation of the muscle contraction and the inadequacy of the lower limb control. To provide support and control of the lower limb, a controlled-brake orthosis is used to aid the partial weight-bearing gait [6]. This orthosis uses kinematic linkages that brace the foot, wrap around the lower and upper leg, and is fitted with controlled brakes at the knee. The orthosis is attached to the pelvis.

To provide the pneumatic power required to operate a motion-support robotic orthosis, various designs have been proposed. A bipedal motion system design uses Pneumatic Muscle Actuators (PMA) constructed of an inner rubber tubing and an outer braided nylon mesh. When the inner tubing is pressurized, it expands, causing the outer mesh to expand radially and at the same time contract longitudinally [7,8]. An hexahedron rubber actuator (HRA) is constructed of four parallelogram plates incorporating rubber bladders and netting [9]. These are located at a joint to form an antagonistic unit. Pressurizing both bladders of the HRA causes the joint to remain straight. A differential pressure between the bladders causes a rotation of the joint. Since there are no sliding components, friction is minimized. Bergamasco et al describe the design of an arm exoskeleton system supported by the shoulder and trunk of the operator and consisting of seven DC servomotor actuators and sensors that wrap the arm [10]. This exoskeleton is used to study the force feedback system as it relates to the "replication" of the sensation of external forces on the operator's arm.

Control of pneumatic actuators can be accomplished by a variety of methods. One method is by using a voice-coil flapper valve and low-friction cylinders [11] with feedback from pressure and position sensors. An Input-Output (I/O) board with analog inputs and outputs is used to read the signals from the pressure and resistor type position sensors, and to provide a voltage output to the flapper valve. Other methods involve direct drive pneumatic servo-actuators where a double acting pneumatic cylinder is controlled by a four-way valve [12], and Pulse-Width-Modulation (PWM) [13]. The PWM is used to control a pneumatic double acting cylinder by using two three-way solenoid valves operated by solid state relays and controlled by an I/O board. The cylinder is attached to a mass that moves horizontally on a low friction slide, and its position is detected by a linear potentiometer. A pneumatic brake mechanism is energized once the mass has reached a desired position.

During the last two years our group at Rutgers University has designed and is currently developing an HME using pneumatic actuation. This system is a quick connecting and removal exoskeleton system that attaches to the foot and hip area of the body, thus "closing" the lower-body kinematics chain. Rather than using multiple actuators per leg, the Rutgers HME uses only two actuators, one for each leg. This system utilizes Variable Air Pressure And Volume (VAPAV) to convert the up and down motion of the human's center of gravity into potential energy, and store this energy in the form of pneumatic pressure. This pneumatic energy is used to supplement the human muscles while running, jogging, bending down, and standing up. Because it supplements the human muscles, the human uses less energy while at the same time having complete control of the exoskeleton system. By using only one actuator per leg, the system is simpler, lighter weight, less bulky, more reliable, and economically more attractive than multi-actuator systems. Since the system uses the human's movement to regenerate, bulky and heavy power packs are eliminated. The user of the HME can field adjust the partial weight-bearing capacity of the system from zero to 100% depending on the user's preference. From preliminary observations, the HME provides the user with freedom of movement approaching that of a human without the system. Control of the system is achieved by using pneumatic sensors implanted into the shoe of the human. In this paper we present the concept of the Rutgers HME, the development of an experimental test fixture and results from preliminary tests with the HME test fixture.

THE RUTGERS HUMAN MUSCLE ENHANCER

The Rutgers HME is shown in Fig. 1 and 2. This concept includes both an upper and lower body HME system. In this paper we only focus on the lower body design. Rather than using multiple actuators per leg, which increase the weight and complexity of the system, the lower body HME uses only two actuators, one for each leg. This system is a quick connecting and removal exoskeleton system that attaches to the foot and hip area of the body.

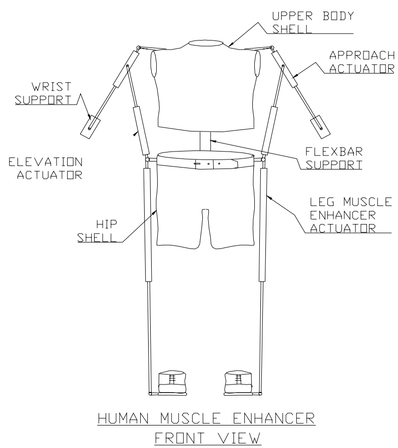

FIGURE 1: Rutgers HME (Front View)

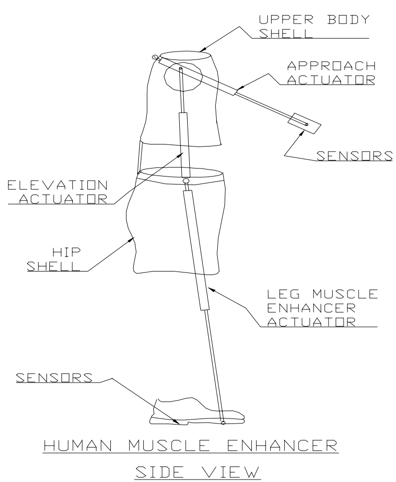

FIGURE 2: Rutgers HME (Side View)

Each shoe is fitted with a snap-on fastener that receives the rod end of the cylinder, which is provided with a ball swivel attachment. The partial body force is supported by the cylinders and is transmitted to the floor, partially bypassing the legs. At the hip area, a belt, which is designed into the hip shell garment worn by the user, is fitted with two snap-on fasteners that receive the body end of the cylinders. The cylinders are designed of fiber-reinforced thermoplastic with an integral linear encoder to provide position sensing. The internal seals, wear ring, and rod bushings are designed from self-lubricating and low-friction materials. As an alternative, a more economical cylinder design can incorporate a lightweight, stainless steel body with an external position sensor. Quick connecting flexible air tubing is attached to the cylinders and connected to the control valves. A miniature portable compressor that supplies a small reservoir located on a backpack or hip sack supplies the air pressure.

The HME system utilizes Variable Air Pressure And Volume (VAPAV) to convert the up and down motion of the human's center of gravity into potential energy, and store this energy in the form of pneumatic pressure. The VAPAV provides the variable spring constant of the actuator. To assist the pressure side of the actuator, the rod side of the cylinder is subjected to vacuum, thus providing additional energy efficiency. This pneumatic energy is used to supplement the human muscles while running, jogging, bending down, and standing up

The system's electronics include a miniature Programmable Logic Controller (PLC) that receives analog and digital signals. The PLC processes these signals and provides outputs to the electro-pneumatic control valves. All control components, power supply, and sensors are mounted on a backpack. The HME is controlled volitionally through sensors strategically located on the human, the garment, and the HME system. This, together with the industry proven reliability of the PLC, provides a system that is reliable, failsafe, and robust.

An alternative to using the PLC is the use of a miniature Pentium PC, D/A and A/D boards, motion controllers, sensor interface boards and a modem card for radio communication with a remote control station. All computers and sensor interface boards are mounted on a backpack and are based on the PC-104 architercture. PC/104 cards are compact modules (3.6 x 3.8 in) that can stack together which eliminate the need for a motherboard, backplane, and/or card cage. Power requirements and signal drive are reduced to meet the needs of the embedded systems. Because the PC/104 is essentially a PC with different form factor, most of the program development tools used for PCs can be used for the PC/104 system.

Miniature position sensors placed at the hip, knee, and ankle joints, and miniature myo-electric or myo-pneumatic sensors embedded in the suit, shoes, and gloves provide signal inputs to the PLC or PC system.

TEST FIXTURE

To test this design concept, a lower body exoskeleton test fixture has been fabricated to provide information that will be used to build a wearable lower body HME. See Fig. 3. The test fixture mimics the human leg with the top cylinder providing the body weight on the leg, either cyclic or step. Another cylinder acts as leg muscles to provide the adjustable human reaction of the leg. The HME cylinder provides the muscle enhancement.

The test fixture is of modular design to provide easy modifications. To minimize friction and the effects of slight assembly misalignments, rod ends are used as revolute joints. They incorporate spherical bearing ends that are self-aligning. The "hip" is loaded by the body-weight cylinder mounted at the terminal end of two vertical and parallel precision hardened shafts. Attached to the "hip" are self-aligning linear recirculating ball bearings that minimize both static and dynamic friction. The angle of the knee is measured by an optical encoder attached to a pulley and cable system. Standard industrial components such as shaft supports, clamp-type shaft collars, rod ends, and precision alloy steel shafts are used to minimize machining. The base, foot, and leg components are 6061-T6 aluminum.

The optical encoder is mounted on one of the vertical shafts. An aircraft cable is attached to the hip and wraps around a pulley attached to the encoder to eliminate slipping. A weight hangs from the end of the cable to remove any slack. As the hip rides up and down the vertical shafts, the knee angle changes. A trigonometric relation provides the relation between the encoder rotation and the knee angle.

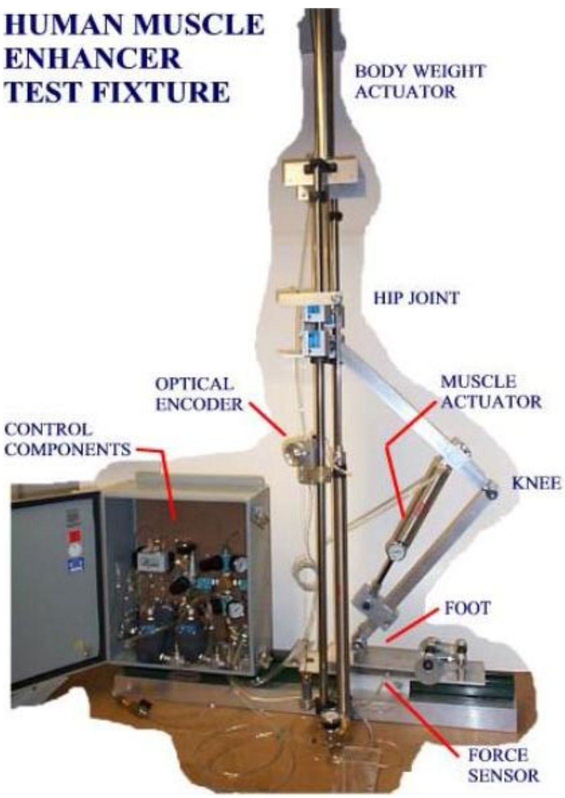

FIGURE 3: HME Test Fixture

The location of the foot relative to the "hip" is adjustable to provide future off-vertical data, if required. The foot design mimics a human foot. It incorporates joints at the ball of the foot and at the ankle. The toe section of the foot is designed to pivot and rest parallel to the "floor" as the foot rotates from dorsiflexion to plantar flexion allowing a sensor to be located under the ball of the foot for data acquisition. Clamp-type design components are used in place of setscrew-type to eliminate shaft damage and to quickly alter the fixture's component settings.

Pneumatics is utilized because it is highly compliant, when compared to electric or hydraulic systems, making the system ideal for dexterous manipulations. It provides high speed and force, and high payload to volume and high payload to weight ratio. Compared to hydraulics, it provides clean power when used with clean dry air. Unlike hydraulics, minute air leaks are tolerable. Pneumatics is readily available, whether the source is stationary or portable. Compact oil-free compressors are available for use in the home, at work, and health facilities. Pneumatics does have some disadvantages. It has poor damping and low stiffness. Many actuators require lubrication, and depending on the application, friction is a concern.

The Rutgers HME pneumatic system is divided into four major circuits. Figure 4 shows the HME part of the circuit.

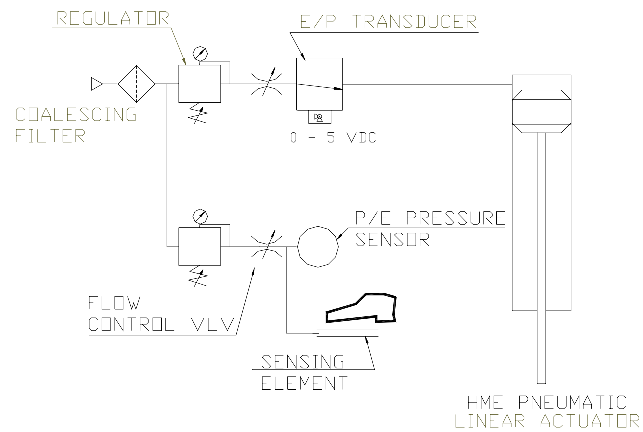

FIGURE 4: Pneumatic Circuit - HME Cylinder and Sensor

The HME actuator circuit together with the Myo-Pneumatic (MP) sensing element provides an output force generated by the HME actuator to counteract the Body Weight force. The pneumatic cylinders used in this test fixture are Bimba® double acting, stainless steel body and rod, with aluminum ends.

A relative force on the MP sensor allows the hip to move up or down at the discretion of the user. The speed with which the hip moves can be controlled by the force applied to the MP sensing element. See Fig.5.

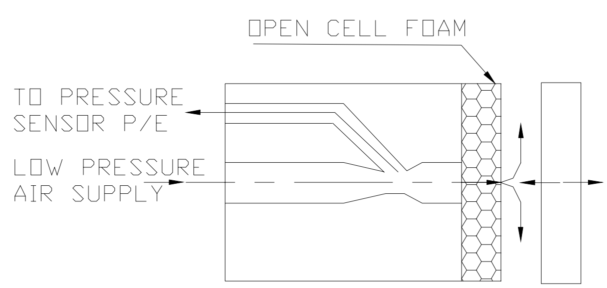

FIGURE 5: Myo-Pneumatic sensor

The MP sensor in the sole of the shoe consists of a block with an air inlet passageway on one side and an outlet jet bleeding from the opposite side. Another air passageway leads away from the jet outlet at an acute angle, providing the sensor output. The outlet jet is provided with an open-cell foam pad to provide a nonlinear resistance to the input force provided by the human. The MP sensor circuit consists of a low pressure regulator upstream of a flow control valve. Because of the acute angle between the input and the output passageways, the MP sensor mimics a venturi by creating a negative pressure of 5mm water gage in the output tubing leading to the P/E sensor when no force is applied on the open-cell foam. As a force is exerted on the foam pad, a backpressure builds in the line to the P/E sensor, providing a voltage output to the input of the I/O board. This design improves the reaction time upon force-release to reach atmospheric pressure in the output tubing. The airflow through the sensor can be regulated by adjusting the pressure regulator or by adjusting the flow control valve.

The leg-muscle (LM) circuit is designed to provide adjustable counter torque at the knee to simulate the subject's partial weight-bearing self-support. See Fig. 6. This is accomplished by setting the LM cylinder initial pressure with the leg in a standing position and presetting the volume of an adjustable auxiliary air chamber connected to the LM cylinder. This provides a counter force to the weight of the leg so that the leg can be moved up or down with minimum effort. For testing purposes, by eliminating the weight of the leg, the HME is counteracting the body weight furnished by the weight cylinder only. The pressure of this system is established by the ideal gas law (PV=mRT). To keep the air mass constant in the LM circuit, a check valve prevents the initial mass of the air from relieving through the pressure regulator. The regulator is set 35 kPa (5 psi) higher than required, to overcome the pressure to "crack" the check valve. The temperature of the air is assumed to remain constant during the cycle. A gage on the air chamber provides a visual indication of the pressure variation during the cycle. As the leg bends down, the LM cylinder retracts increasing the trapped air pressure. By providing a predetermined chamber volume, the LM can provide fairly constant torque at the knee. Decreasing the chamber volume provides increased resistance; while increasing the chamber volume provides decreased resistance. A pressure to voltage (P/E) sensor connected to this circuit provides the Leg Muscle (LM) input signal to the I/O analog port.

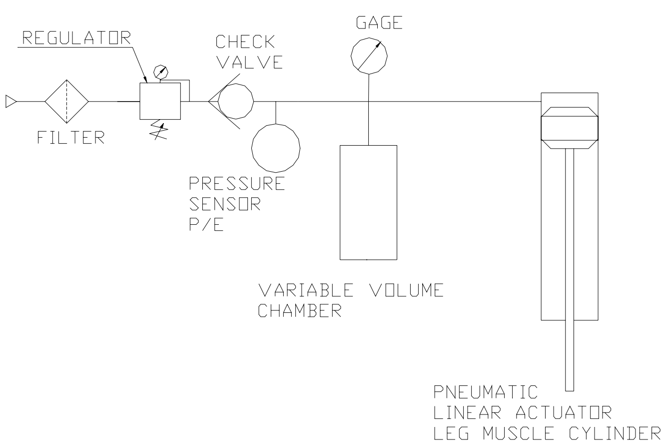

FIGURE 6: Pneumatic Circuit - Leg Muscle

The Body Weight (BW) pneumatic circuit is illustrated in Fig. 7. Air to the circuit is conditioned by a coalescing filter with a sub micron element to remove contaminants that may affect the control valve, and is regulated to 280 kPa (40 psig). The control valve is a ControlAir® Inc type 500-CF E/P transducer with a flow rate of 7.6 m^3/hr, terminal based linearity of ±1.5% of span, and repeatability of less than .5% of span. The control valve converts an input signal of 0 to 5 VDC to a linearly proportional range of 14 to 420 kPa (2 – 60 psi). This valve was chosen because of its low cost, industrial duty, easily field adjustable span and zero adjustment. It is field reversible and is readily available. This control valve is a force balance device that uses a voice coil suspended in the magnetic field of a permanent magnet. When current flows through the coil, it affects the coil's movement, creating a pilot back pressure that causes a proportional output pressure.

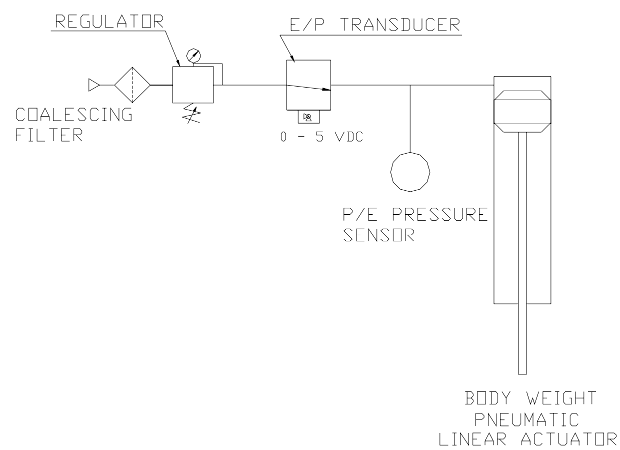

FIGURE 7: Pneumatic Circuit – Body Weight

The controls hardware for the HME test fixture consists of two E/P electro-pneumatic transducers that receive input from pressure and position sensors, and provide air pressure output to the actuators. An optical encoder tracks the knee joint angle and actuator position. A computer with an I/O and encoder card provides sample time data acquisition, and overall control of the system. The I/O board is a Datel® PC-412A featuring 4 analog output channels, 12-bit D/A resolution, and 8 differential analog input channels with a conversion period of 7 µs and a 12-bit A/D resolution. The analog output current is ±5mA with short circuit protection. Trigger control is provided by a software programmable 82C54-interval timer. A/D memory architecture is FIFO with a capacity of 512 A/D samples. The US Digital® PC7166 PC to 4-axis incremental encoder interface card features 4 channels, pre-loadable up/down 24 bit counters, X4 resolution multiplier, and a maximum count frequency of 10 MHz. The HP® HEDS-5500 optical incremental encoder features two channel quadrature output with a resolution of 1024 counts per revolution. Figure 8 shows a schematic of the HME controller block diagram.

EXPERIMENTAL RESULTS

The HME test fixture is being tested to simulate the responsiveness of the system. It has been tested using step and sinusoidal inputs. Tests were conducted using feedback from the optical encoder to perform closed loop position control. A representative result from the closed loop position control

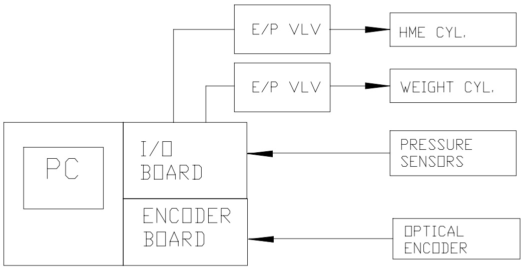

FIGURE 8: Controls Block Diagram

experiments is shown in Fig. 9. Starting with the fixture leg in the upper-most position, the knee angle was set to a desired value and the weight cylinder was subjected to a desired constant pressure. Using a PID controller with fixed gains, the HME cylinder counteracted the weight cylinder to provide the desired knee angle positions. With 180° representing the vertical leg position, the controller was set to a knee angle of 80°, 100°, and 120°. The HME was able to reach these positions with a settling time of less than 1.5 seconds. Overshoot and offset are evident for the 120° and 100° setpoints. See Fig. 9. By using variable PID gains, better results were obtained, but at the expense of longer settling times. See Fig.10.

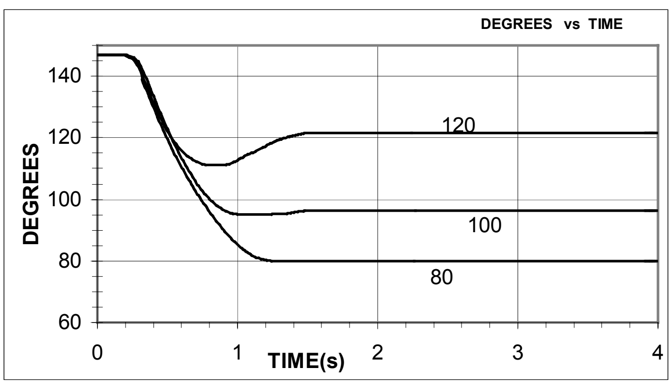

FIGURE 9: Step Response for Constant PID Control

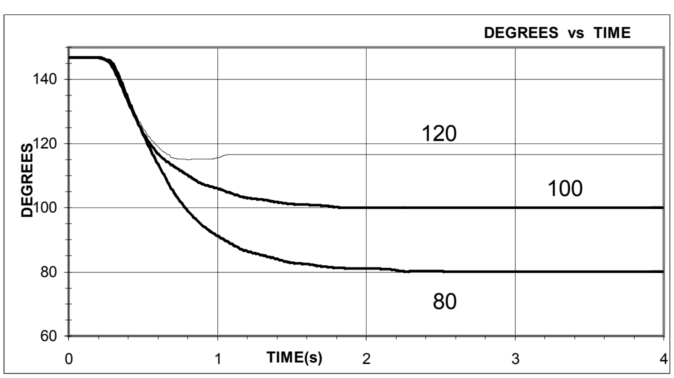

FIGURE 10: Step Response for Variable PID Control

Figures 11 and 12 show the response of the HME to a sinusoidal input weight at two different frequencies and a knee angle setpoint of 100°. The HME is able to hold position to ±5°.

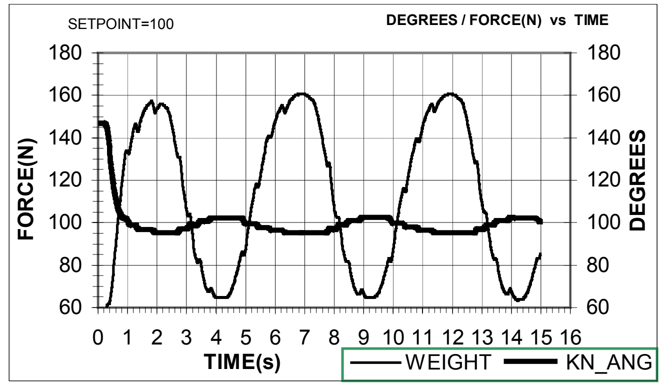

FIGURE 11: Response to Sine Input - Variable PID

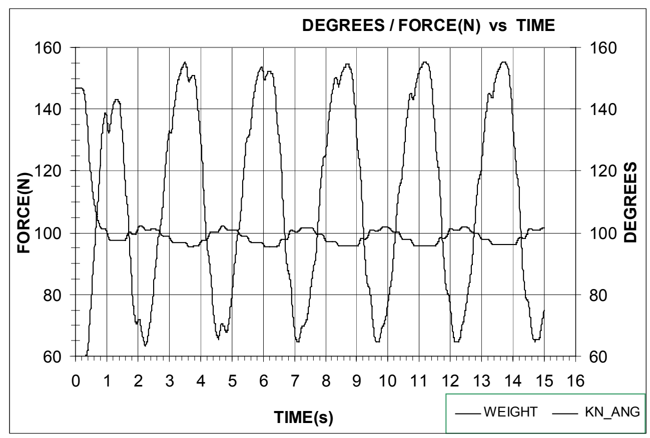

FIGURE 12: Response to Sine Input - Variable PID

To provide an energy efficient system, a Variable Air Pressure And Vacuum (VAPAV) circuit was designed into the HME system. Since the HME actuator is working against gravity and since the rod end of the cylinder is not used in controlling the action of the HME, this port was subjected to vacuum, thus supplementing the pressure side of the HME. See Fig. 13. During this test the HME control valve was set at a fixed value to provide a constant force, and the weight cylinder was operated to provide a sinusoidal load. With VAPAV minimal additional energy is required while without, additional pressure is required with each cycle to keep the knee angle within a horizontal band.

Multiple open loop tests were also conducted using the MP sensor. Here the operator controlled the action of the HME to simulate the rise, sit, or move and hold positions at intermediate points. Applying pressure to the foam pad of the MP sensor controlled the HME. As illustrated in Fig. 14, the action was smooth and consistent, with little or no overshoot. Fig.14 shows that a human subject can have fairly accurate control of the HME in stopping at desired intermediate knee angles when moving at a knee angle rotation of approximately 40° per second. A rehabilitating subject would be moving at a much slower rate.

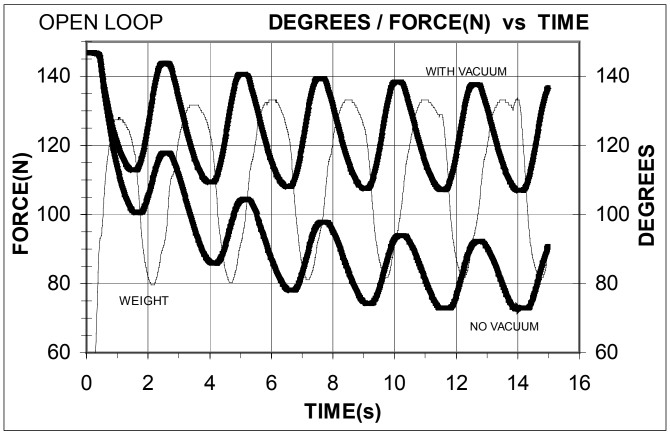

FIGURE 13: Response - Vacuum vs No Vacuum Assist

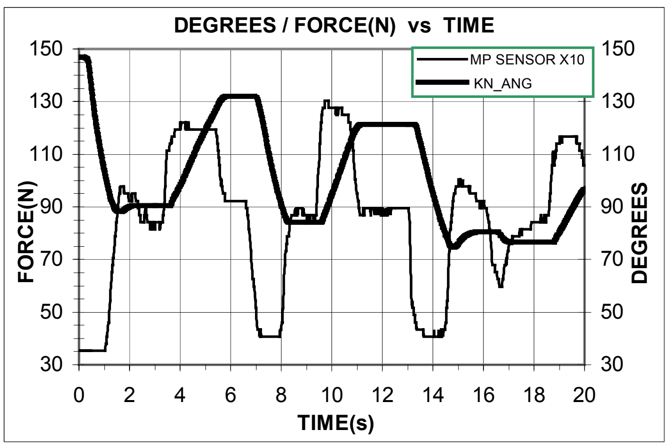

FIGURE 14: Open Loop MP Sensor Control

CONCLUSIONS AND FUTURE WORK

The Rutgers Human Muscle Enhancer is an assistive system that will augment the muscle capabilities of subjects requiring partial weight bearing support. Its design is lightweight, reliable, simple, easy to wear and remove, compliant, and an economical alternative to multi-actuator systems.

Testing of the HME fixture is continuing in the areas of control using variable loads during a cycle to simulate the lifting or dropping of a weight, and using sensors other than myo-pneumatic to check the behavior during a walk, rise, and sit cycle. Sensors may include myo-electric, capacitive, and optical. Future testing will also include the biomimetic control of the HME by using multi-sensors located at specific parts of the leg, as yet to be determined, to check the feasibility of using volitional and non-volitional leg signals to generate a signal response matrix [14]. The control valves need to be miniaturized to reduce volume, and weight. A prototype HME needs to be fitted on a subject to test and fine-tune the design. This will also require the fine tuning of a design of a foot attachment component that can be used with various shoe designs by males, females, young, and adult subjects. Also, the quick connecting hip belt attachment components need refinement by providing an integral pants garment that is comfortable, easy to wear and remove; that is lightweight, and that will provide adequate support.

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