Proceedings of IMECE2004
2004 ASME International Mechanical Engineering Congress
Anaheim, California, USA, November 13-19, 2004

IMECE2004-59472

HUMAN STEP REHABILITATION USING A ROBOT ATTACHED TO THE PELVIS

D. Aoyagi[1] **W.E. Ichinose**[1] **J.T. Lin**[1] **K. Ngai**[1] **S.J. Harkema**[2] **D.J. Reinkensmeyer**[1] **J.E. Bobrow**[1]

[1]Department of Mechanical and Aerospace Engineering
University of California, Irvine

[2]Brain Research Institute
University of California, Los Angeles

ABSTRACT

This paper describes a new robot capable of manipulating pelvic motion during human step training on a treadmill. The robot, PAM, (Pelvic Assist manipulator) uses two, pneumatically actuated subsystems arranged in a tripod configuration to measure and control the pelvis of a person during body weight supported stepping on a treadmill. The device can be used in a passive mode to record pelvic trajectories, either specified manually by a therapist or pre-recorded from unimpaired subjects, then replay these trajectories using a non-linear force control algorithm. The control laws of the robot are presented, along with data that demonstrate the ability of the device to record and replay the pelvic motions that occur during normal walking.

INTRODUCTION

Gait training with body weight support (BWS) and manual assistance of the legs and pelvis is a promising new therapy method for patients after spinal cord injury or stroke [1, 2]. It is hypothesized that the repetitive patterns of sensory inputs during gait training stimulate the spinal cord, encouraging it to functionally reorganize itself. However, the training is labor intensive, requiring two to three therapists to assist the patient's legs and torso and to operate the treadmill and BWS during each training session. In addition, the assistance, and thus the pattern of sensory input to the nervous system, can vary greatly between trainers and sessions. Robotic devices can potentially improve the quality and quantity of training, providing sensory input that is repeatable and reproducible for extended period of time with reduced load on the therapists.

There are several research groups developing such robotic devices. The Lokomat is a motorized exoskeleton, consisting of four rotary joints driven by DC motors via ball screws, which can manipulate a patient's legs in gait-like trajectories [3]. The Mechanized Gait Trainer (MGT) can also move a patient's legs in a gait-like pattern by driving two foot plates connected to a double crank and rocker system that is actuated by an induction motor via a planetary gear system [4]. ARTHuR has two linear motors and a two bar linkage mechanism to achieve good back-drivability and force control capability during stepping [5].

These devices have primarily focused on the motion of the legs. The Lokomat, for example, has four rotary degrees of freedom (DOF) for leg motion, namely left and right hip and knee flexion/extension joints, but the subject's pelvis is allowed to move only passively in the vertical direction. Pelvic rotations and horizontal translation are restricted and the resulting motion is not naturalistic. However, pelvic motion plays an important role in locomotion. During unconstrained normal locomotion the pelvis undergoes three translational displacements and three angular displacements, which are coupled to step rate and stride length [6]. Lateral pelvic motion is especially important because it assists with the load shifting between legs, generating the corresponding sensory inputs that drive the locomotor control circuits.

This paper describes the development of a robotic device, called PAM (Pelvic Assist Manipulator), that can measure and manipulate naturalistic pelvic motion during step training on a treadmill [7]. Our hypotheses are that a robotic device that ac-

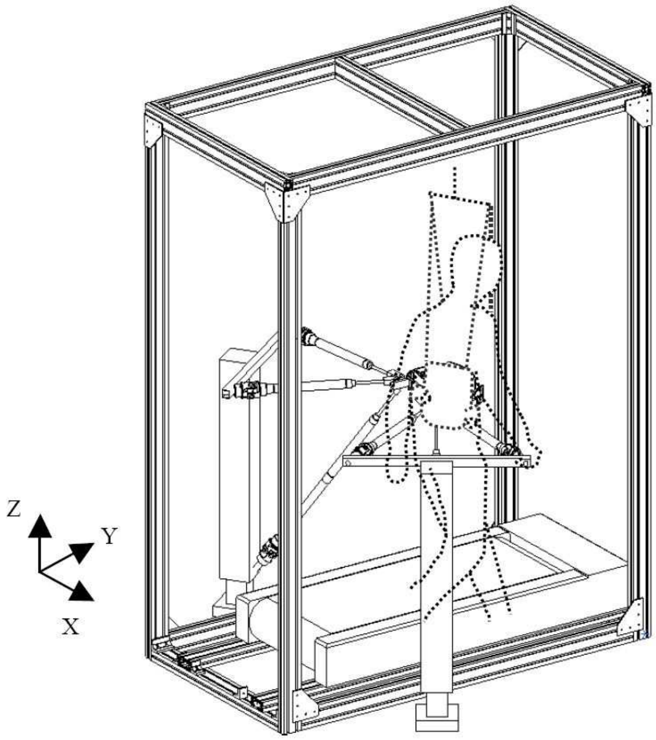

Figure 1. CONCEPTUAL DRAWING OF PELVIC ASSIST MANIPULATOR (PAM).

commodates naturalistic movements will lead to better functional recovery for the patient, and that assisting in gait training only as needed will be more effective than a fixed amount of assistance. Such a robotic device must have many DOF with good force control ability including backdrivability, which presents greater technical challenges for robot design. The robot has to be safe, most of all. It must be comfortably attachable to and quickly detachable from the subject. We would like to provide human therapists with easy access to the subject, and the subject with room for arm swing and unobstructed field of view. Our goal is to use PAM in concert with the leg robot that we have developed (ARTHuR), with PAM manipulating the pelvis and ARTHuR the legs.

MECHANICAL DESIGN

PAM consists of a pair of three DOF pneumatic robots that attach to the back of a belt worn by the subject (Fig. 1 and 2). Each robot has three pneumatic cylinders arranged in a tripod configuration supported by a T-shaped support pillar via ball joints. The belt width is adjustable and the supporting pillars are height adjustable to accommodate various hip sizes and hip heights. The three cylinders are connected by a custom-designed linkage that implements a spherical joint. The cylinder axes intersect at a point. As a result, PAM has 5 DOF, namely three translations (side-to-side, forward-and-back, up-and-down) and two rotations (pelvic rotation and obliquity). Pelvic tilt cannot be measured or controlled. A separate overhead BWS system unloads the patient as desired. The two subsystems are placed at an angle to give the therapist access to the subject from the sides and behind as needed. They are attached to the belt behind the subject to provide room for arm swing, and can also be detached and separated to make sufficient spacing to allow the subject to enter the device from a wheelchair.

Figure 2. PICTURE OF PELVIC ASSIST MANIPULATOR (PAM) AND ARTHUR 2.0.

We chose pneumatic cylinders to actuate the device because they provide higher force per weight ratio than geared electric motors, and yet are relatively affordable (less than $1000 per DOF, including cylinder, pressure and position sensors, servovalves and venting valve for safety). Although they require a pressure regulator and servovalves to operate as well as the tubes to interconnect them, the actual moving parts can be made light. Supply of compressed air should be readily available at institutions or laboratories where this device is likely to be installed, or we can use a portable air compressor unit. The maximum supply pressure and the flow rate will limit the maximum force and power output of the cylinders. The force tracking control law described in the latter section compensates for the nonlinear dynamics introduced by the pneumatics.

FORCE TRACKING CONTROLLER

We adopted the hierarchical control strategy to control the overall motion of the robot [8]. The force-tracking controller we developed for the pneumatic actuator acts as the inner loop in the hierarchy (Fig. 3). We model the compressive air flow dynamics for each cylinder, and use pressure sensors on both sides of the

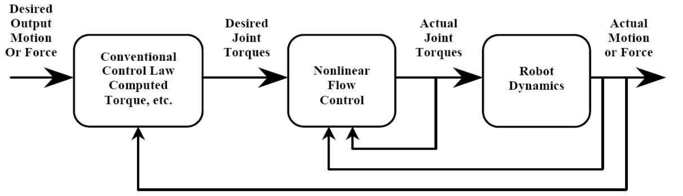

Figure 3. HIERARCHICAL NONLINEAR PNEUMATIC CONTROL LAW.

piston for feedback to achieve force control.

Theoretically only one servovalve is required to control the net force output of a cylinder, because only the difference of the pressures needs to be controlled, not the two independent pressures. However, such an approach with one servovalve per cylinder can lead to high pressures on both sides of the piston, because in our setup there is always some air leakage through the servovalve from the supply to the chamber, which builds up in time to cause high pressures. Unnecessarily high pressures can cause poorer performance in the backdrivable mode, where desired output force is set to zero and quick venting is required when the piston is moved by an external force. So we chose to use two servovalves per cylinder to control each side of the piston independently. This approach allowed us to keep the pressures on both sides of the piston low, or high if desired. Keeping the pressures low means that we need to move a smaller amount of air in and out of the cylinders particularly in the backdrivable mode. With this approach, we could achieve smoother and quicker performance, while consuming a smaller amount of compressed air.

Now we describe our nonlinear force control algorithm. For each side of the piston chamber in Fig. 4, we can find the dynamics of air flow and the chamber pressure by considering a power balance of the system [8].

$$c_p T\dot{m} - p\dot{v} + \dot{Q} = \frac{c_v}{R}\frac{d}{dt}(pv) \tag{1}$$

where

p : pressure inside the chamber
v : volume of the chamber
$\dot{m}$: mass flow rate of air into chamber
T : air temperature
R : gas constant
$\dot{Q}$: heat transfer rate through the cylinder wall
c_p : constant pressure specific heats of air
c_v : constant volume specific heats of air.

In Eqn. (1), $c_p T\dot{m}$ is the internal energy of the air flowing into the chamber, $p\dot{v}$ is the power output by the moving piston, and $\frac{c_v}{R}\frac{d}{dt}(pv)$ is the time derivative of the total internal energy of the air in the chamber. We measure p by a pressure sensor, and compute v from the piston position measured by a potentiometer. We assume $\dot{Q} = 0$ because the heat transfer process has much slower

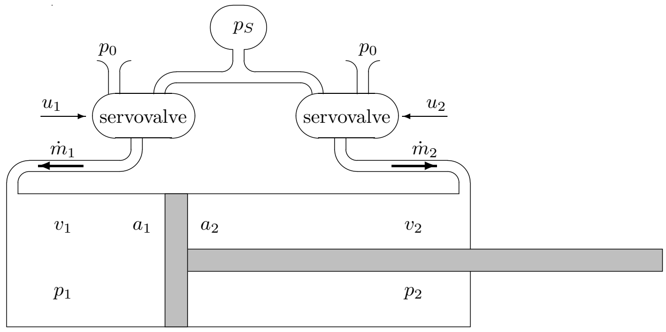

Figure 4. SCHEMATIC DIAGRAM OF A PNEUMATIC CYLINDER.

time constant than the air flow dynamics. We can change the form of Eqn. (1) by using $\frac{c_p}{c_v} \equiv \kappa$ and the fact $R = c_p - c_v$, to obtain the differential equation for the compressed air in the chamber.

$$\dot{p} = \kappa RT\frac{\dot{m}}{v} - \kappa\frac{p\dot{v}}{v} \tag{2}$$

The mass flow rate $\dot{m}$ is controlled by the servovalve, which has its own dynamics. In general the governing equation for the flow rate through the servovalve is described as nonlinear functions of valve spool position, supply pressure, and chamber pressure. However, we ignore those dynamics and nonlinearities. To simplify, we assume the mass flow rate is proportional to the control current u driving the servovalve. The model for the compressed air flow through the servovalve is then

$$\dot{m} = c_f u \tag{3}$$

where c_f is the servovalve coefficient. Now, knowing the area of the piston is a, we can write the force produced by the piston chamber.

$$f = pa \tag{4}$$

Differentiating Eqn. (4), we get

$$\dot{f} = \dot{p}a. \tag{5}$$

Combining Eqn. (2), (3), and (5), we get

$$\dot{f} = aRT\kappa\frac{c_f}{v}u - a\kappa\frac{p\dot{v}}{v}. \tag{6}$$

Assuming the air temperature is constant, we can re-define constants.

$$\dot{f} = \alpha\frac{a}{v}u - \kappa\frac{ap\dot{v}}{v} \tag{7}$$

We set the control to

$$u = \{k_P(f - f_d) + k_D \dot{f}_d\}\frac{v}{a} + k_V p\dot{v} \quad (8)$$

where f_d is the desired force by the chamber, and k_P, k_V and k_D are the design parameters (gains). Plugging the feedback control into Eqn. (7), we get

$$\dot{f} = \alpha\{k_P(f - f_d) + k_D \dot{f}_d\} + (\alpha k_V - \kappa)\frac{ap\dot{v}}{v}. \quad (9)$$

If we choose $k_D = \frac{1}{\alpha}$ and $k_V = \frac{\kappa}{\alpha}$, then Eqn. (9) becomes

$$\dot{f} - \dot{f}_d = \alpha k_P(f - f_d). \quad (10)$$

That means for a smooth time trajecotry of desired force $f_d(t)$,

$$f(t) \rightarrow f_d(t) \text{ as } t \rightarrow \infty \quad (11)$$

for some $k_P > 0$. Experimentally, we can adjust the gains manually until good force tracking is achieved. For implementation purposes, we ignore the term with the derivative of the desired force, setting $k_D = 0$. Although the tracking is not guaranteed anymore with $k_D = 0$, we ignored it because f_d is not smooth sometimes and the derivative of it can introduce additional noise to the system. As a result, some phase lag is typically observed.

Now, we look at both sides of the piston. Ignoring the friction in the piston, the net output force f is given by

$$f = p_1 a_1 - p_2 a_2 - p_0 a_0 \quad (12)$$

where
$i = 1, 2$: subscript referring to sides of cylinder chamber,
p_0 : atmospheric pressure,
a_0 : cross-sectional area of the piston rod ($a_0 = a_1 - a_2$).
Given a desired net force of the piston, f_d, we can set desired forces for each chamber.

$$\left.\begin{array}{l} f_{1d} = f_{10} + f_d \\ f_{2d} = f_{20} \end{array}\right\} \text{ if } f_d \geq 0$$
$$\left.\begin{array}{l} f_{1d} = f_{10} \\ f_{2d} = f_{20} - f_d \end{array}\right\} \text{ if } f_d < 0 \quad (13)$$

where f_{10} and f_{20} are the nominal pressures for each chamber, satisfying $f_{10} - f_{20} = p_0 a_0$. We adjusted f_{10} and f_{20} experimentally for smoother operation. The desired force for each chamber

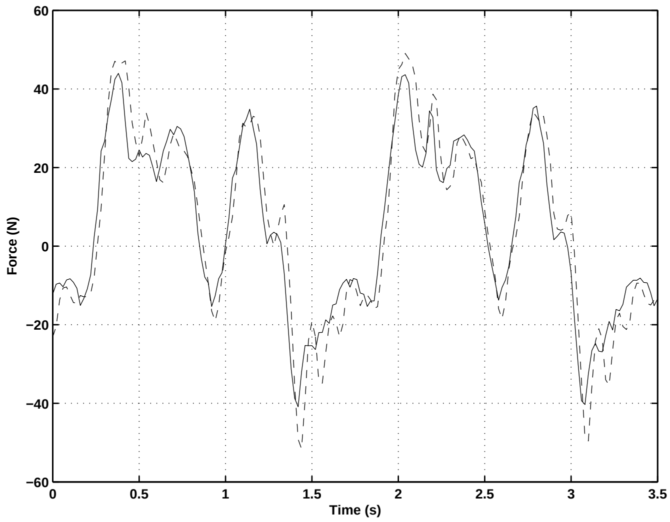

Figure 5. PNEUMATIC ACTUATOR FORCE TRACKING DURING THE TEACH-AND-PLAY. SOLID LINE: DESIRED FORCE, DASHED LINE: ACTUAL FORCE.

is computed by Eqn. (13), then passed on to the control law in Eqn. (8). As the actual force on each chamber tracks the desired force trajectory, the net force of the piston also tracks the desired trajectory. We used Matlab Simulink and xPC system from Mathworks for the implementation of real-time control task.

During an early stage of applying the control law, we encountered severe vibration problem. The pressure feedback loop in the control law picked up and amplified oscillations, keeping us from tuning up the gains. This may be partly because of the system dynamics we ignored, such as the resonance of the servovalve and the pressure waves in the tubing. Due to this problem, we applied a digital filter to the control signal in order to achieve satisfactory performance. A first order low pass filter with time constant of 0.03 second, and a butterworth filter with cutoff frequency at 90 Hz are used. Although the introduction of filter limits the response time of the controller, we were able to achieve bandwidth of more than 5 Hz. A typical tracking performance is shown in Fig. 5.

SAFETY DESIGN

Since PAM will be attached to and interacting with humans, safety is an extremely important issue. Our design approach is to incorporate redundant safety features. First of all, the supply air pressure is regulated (typically at 40-50 PSI), so that the maximum force the actuators can possibly produce is physically limited, if anything goes wrong. Also the compressed air supply has restricted flow rate, which means the mechanical power the robot can physically output is limited. That can be explained by the power balance in Eqn. (1). If the flow rate is bounded by some $\dot{m}_{max}$, the energy input to the system is bounded. Since the internal energy stored in the system is kept small by setting the nominal pressures f_{10} and f_{20} low, the mechanical power output is also bounded. Thus, the robot can generate large forces at slow speeds, but only small forces at high speeds, so in the event of a valve failure, the device does not move rapidly. There are two emergency stop switches, one for the operator/therapist and the other for the subject, which can cut the electric current that keeps the main supply valve open against the return spring. As soon as the switch is pressed, all the pneumatic cylinders are vented to atmosphere. By pushing the switch, both the subject and the operator can stop the robot anytime they want to. Once vented, the robot becomes mechanically passive with its cylinders acting like light dampers. Although some of the weight of the robot will rest on the subject in such a case, it is not heavy enough to cause injury.

Our real-time control software has several safety features. We limit the maximum force PAM can produce by software in addition to the physical limits explained above. If the robot moves too fast by itself or by some external force, i.e., if the velocity goes above a certain threshold for any reason, the software disengages the main supply valve, causing the robot to become passive. Having redundant DOF (six joint DOF for five task space DOF), PAM can detect any inconsistency of its joint kinematics, for example due to sensor failure. If the computed distance between the two spherical joints attached to the belt does not match the real physical distance, which indicates the belt attachment is broken or position sensors are malfunctioning, PAM vents the main valve. When the force tracking controller is engaged and everything is working correctly, the force tracking error should be reasonably small. Large force tracking error is an indication of some kind of abnormality, such as pressure sensor failure or punctured tubing. So, if PAM detects force tracking error larger than some threshold, it vents the main valve. We also installed a watchdog timer (Analog Devices ADM695) that monitors the pulse signal from the computer and vents the main valve if the pulse stops coming.

POSITION CONTROLLER DESIGN

We constructed a PD position control law on top of the force tracking controller. Since the force tracking controller works on each cylinder level (joint space), we solved the kinematics of the robot in order to apply desired forces (three translational and two rotational) on the belt (task space). The Jacobian matrix J^T relates the cylinder force and the task space force.

$$\mathbf{f}_d = \mathbf{J}^T \tau_d \tag{14}$$

where τ_d is the desired force in task space, and $\mathbf{f}_d$ is the desired force in joint space.

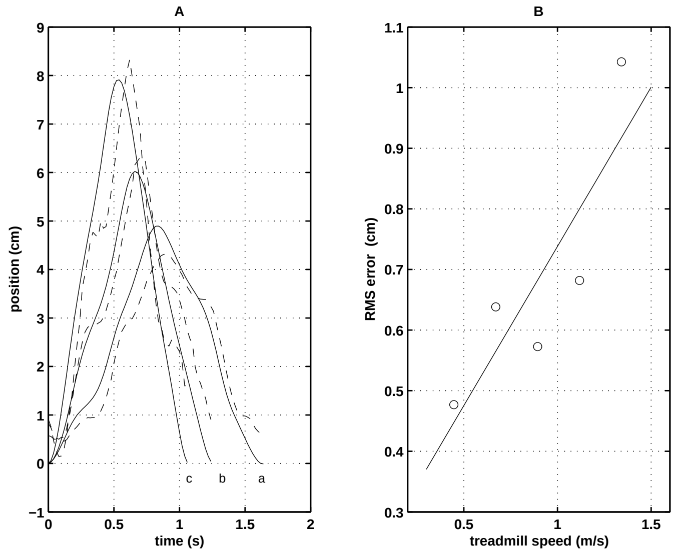

Figure 6. POSITION TRACKING (TEACH-AND-REPLAY) DATA. A) SOLID LINE: ONE CYCLE OF DESIRED SIDE-TO-SIDE TRAJECTORY, DASHED LINE: ACTUAL SIDE-TO-SIDE TRAJECTORY WHEN PAM MOVED A 100-LB PUNCHING BAG, a: 0.45 M/S (1 MPH), b: 0.89 M/S (2 MPH), c: 1.34 M/S (3 MPH). B) ROOT-MEAN-SQUARE TRACKING ERROR VERSUS THE TREADMILL SPEED AT WHICH THE DESIRED TRAJECTORY WAS RECORDED.

Then we constructed a PD control law in the task space:

$$\tau_d = \mathbf{G}_P(\mathbf{x} - \mathbf{x}_d) + \mathbf{G}_D(\dot{\mathbf{x}} - \dot{\mathbf{x}}_d) \tag{15}$$

where $\mathbf{x}$ is the actual position trajectory of the attachment belt, and $\mathbf{x}_d$ is the desired position trajectory of the attachment belt. Equation (15) defines the desired correctional force to be applied by the attachment belt to the subject. Equation (14) then gives the corresponding joint (cylinder) forces, which are passed on to the force tracking controller. There is no feed-forward term or computed-torque type term. The two gains, $\mathbf{G}_P$ and $\mathbf{G}_D$, are adjusted for each component of the five pelvic DOF separately, that is, the both gain matrices are diagonal.

TEACH-AND-REPLAY RESULTS

One of the advantages of having a force tracking controller is that the robot can act as a kind of motion capture device when the robot becomes backdrivable with all the desired actuator forces set to zero. We conducted an experiment to demonstrate PAMs ability as a teach-and-replay device. In this experiment an unimpaired subject walked on the treadmill at speeds ranging from 0.45 m/s (1 MPH) to 1.34 m/s (3 MPH) while PAM operated in the backdrivable mode. We recorded the position trajectory for 50 seconds. We then identified step cycles based on threshold crossings and took an average of the measured step data over all cycles, producing a mean pelvic trajectory at each treadmill speed. We then replayed the repeating sequence of this trajectory against a 100-pound (45.4 kg), bungee-suspended punching bag with the PD controller described above. We did not model the dynamics of the attachment belt and the suspended punching bag. Figure (6) shows the tracking for the left-to-right translational component of the desired pelvic position trajectory for one period of the gait cycle at three different speeds. The RMS tracking error was less than 1 cm for walking up to 1.5 m/s. Figure (6) also shows that side-to-side motion was substantial during walking, and varied with walking speed, supporting our hypothesis that allowing/controlling pelvic motion will be an important factor for improving gait rehabilitation.

DISCUSSION/CONCLUSION

Robotic devices can potentially provide accessible and consistent rehabilitation therapy for extended periods of time beyond the limitations of conventional human-regulated therapy. We are developing a robotic device, Pelvic Assist Manipulator (PAM), that can attach to and manipulate human pelvis during gait training on a treadmill. PAM has five degrees of freedom and utilizes pneumatic actuators for high force per weight ratio and cost performance. Our nonlinear control algorithm allows PAM to exhibit good force controllability including backdrivability, while redundant safety features monitor the system for malfunctioning. We have implemented a hierarchical control strategy with PD pelvic position control being the top level, and nonlinear force control for each piston chamber the lowest level. We present experimental data to demonstrate that PAM can record pelvic motion during stepping and then replay those trajectories against a large mass. PAM will be a useful tool in testing rehabilitation strategies, including the optimal motion control strategy proposed by Wang [9]. By providing measurement and control over naturalistic pelvic motion, PAM has the potential to improve gait training in quality and quantity.

ACKNOWLEDGMENT

Supported by NIST ATP 00-00-4906.

REFERENCES

[1] Werner, C., von Frankenberg, S., Treig, T., Konrad, M., and Hesse, S., 2002. "Treadmill training with partial body weight support and an electromechanical gait trainer for restoration of gait in subacute stroke patients - a randomized crossover study". Stroke, **33** (12) Dec , pp. 2895–2901.

[2] Edgerton, V., de Leon, R., Harkema, S., Hodgson, J., London, N., Reinkensmeyer, D., Roy, R., Talmadge, R., Tillakaratne, N., Timoszyk, W., and Tobin, A., 2001. "Retraining the injured spinal cord". Journal of Physiology-London, **533** (1) May , pp. 15–22.

[3] Jezernik, S., Colombo, G., Keller, T., Frueh, H., and Morari, M., 2003. "Robotic orthosis lokomat: A rehabilitation and research tool". Neuromodulation, **6** (2) Apr , pp. 108–115.

[4] Hesse, S., and Uhlenbrock, D., 2000. "A mechanized gait trainer for restoration of gait". Journal of Rehabilitation Research and Development, **37** (6) Nov-Dec , pp. 701–708.

[5] Reinkensmeyer, D., Wynne, J., and Harkema, S., 2002. "A robotic tool for studying locomotor adaptation and rehabilitation". *Proceedings of the Second Joint Meeting of the IEEE Engineering in Medicine and Biology Society and the Biomedical Engineering Society, EMBS/BMES Conference* October 23-26 , pp. 2353–2354.

[6] Inman, V., Ralston, H., and Todd, F., 1986. *Human Walking*. Williams & Wilkins, Baltimore, pp. 41–45.

[7] Ichinose, W., Reinkensmeyer, D., Aoyagi, D., Lin, J., Ngai, K., Edgerton, V., Harkema, S., and Bobrow, J., 2003. "A robotic device for measuring and controlling pelvic motion during locomotor rehabilitation". *Proceedings of the 2003 IEEE Engineering in Medicine and Biology Society Meeting* , pp. 1690–1693.

[8] McDonell, B., and Bobrow, J., 1998. "Modeling, identification, and control of a pneumatically actuated, force controllable robot". *IEEE Transactions on Robotics and Automation*, **14** , pp. 732–742.

[9] Wang, C., Bobrow, J., and Reinkensmeyer, D., 2001. "Swinging from the hip: use of dynamic motion optimization in the design of robotic gait rehabilitation". *Proceedings 2001 IEEE International Conference on Robotics and Automation* , pp. 1433–1438.