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A ROBOTIC DEVICE FOR MEASURING AND CONTROLLING PELVIC MOTION DURING LOCOMOTOR REHABILITATION

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Abstract- **This paper describes a robotic device for measuring and manipulating pelvic motion during step training on a treadmill. "PAM" (Pelvic Assist Manipulator) uses two, three-degree-of-freedom, pneumatic robots 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. Data are presented that demonstrate the ability of the device to record and replay the pelvic motions that occur during normal walking.**

Keywords – **Locomotion, rehabilitation, robotics**

I. INTRODUCTION

Recent research has suggested that the mammalian spinal cord has a remarkable capacity to learn, and thus that it may be possible to teach individuals with spinal cord injury to step with appropriate sensory motor training [1]. The key characteristics of this training are thought to be partial body weight support (BWS), and assistance of torso and leg movements during stepping on a treadmill. It is hypothesized that the spinal cord can functionally reorganize itself in response to specific patterns of proprioceptive input repetitively provided to it during training.

Such locomotor training is currently labor intensive, requiring up to four trainers to assist in leg and pelvic motion and to operate the treadmill and BWS system. Recognizing the potential benefits of automating the training, several groups are developing robotic devices that can assist in leg movement. The Lokomat consists of four rotary joints, driven by precision ball screws that are connected to DC motors, which are mounted onto a motorized exoskeleton that manipulate a patient's legs in gait-like trajectories [2]. The Mechanized Gait Trainer (MGT) is comprised of two foot plates connected to a double crank and rocker system that is singly actuated by an induction motor via a planetary gear system and drives a patient's legs in a walking pattern [3]. ARTHuR makes use of a linear motor and a two DOF mechanism to measure and manipulate leg movement during stepping with good backdriveability and force control [4]. Other devices under development include HealthSouth's Autoambulator, and a more sophisticated version of the MGT that can move the footplates along arbitrary three degree-of-freedom (DOF) trajectories.

These initial gait-training devices have focused primarily on controlling leg movement. However, pelvic motion also plays an important role in normal locomotion. During unconstrained locomotion the pelvis undergoes three translational displacements and three angular displacements, which are tightly coupled to step rate and stride length parameters [5]. The Lokomat allows unrestricted movement in the vertical direction but restricts pelvic rotation, pelvic obliquity, and horizontal translation of the pelvis. The MGT has taken the simplified approach of moving the torso with a single DOF mechanism along fixed horizontal and vertical trajectories that approximate those achieved during normal stepping. Such a fixed trajectory cannot be optimal for every patient. In addition, this approach requires the same torso motion to be applied regardless of the stage of recovery of the patient. Thus, both of these devices are incapable of direct control or recording of pelvic movements. Patient-specific torso motions may be useful for generating desired gait patterns, as recently

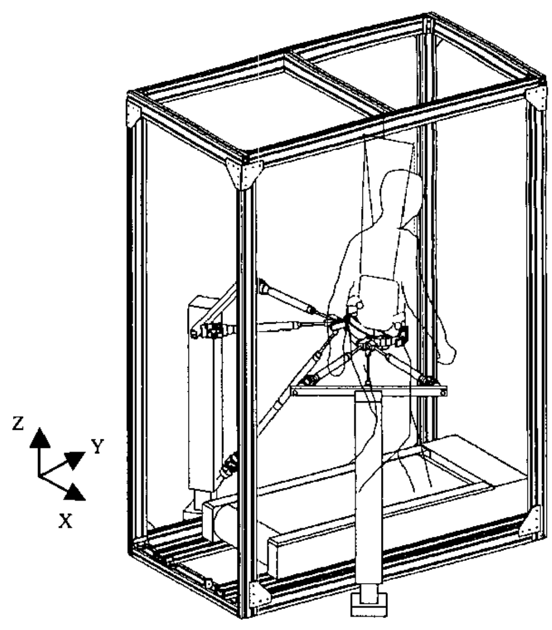


Fig. 1 Pelvic Assist Manipulator (PAM). Two three-degree-of-freedom pneumatic robots are mounted on adjustable pillars and attach to the back of a belt worn by the subject.

demonstrated using dynamic motion optimization techniques [6].

This paper describes the development of a robotic device that can measure and manipulate naturalistic motions of the pelvis. A key design goal was to create a device that exhibited good backdriveability, defined as low intrinsic endpoint mechanical impedance [7], or accurate reproduction at the input end of a mechanical transmission of a force or motion that is applied at the output end [8]. Good backdriveability offers several important benefits for robotic therapy devices [4], including the ability for the device to act as a passive motion capture device. In such a passive motion capture mode, the patient's movement ability can be quantified, and the therapist can manually specify desired, patient-specific training motions for the device.

II. METHODOLOGY

A. Control Design

Our design criteria for a robotic device for assisting in pelvic motion during step training are:

- Accommodate and control natural pelvic motion
- Exhibit good backdriveability
- Do not obstruct arm swing or visual field
- Allow easy entrance and exit for the subject
- Provide therapist with access to the subject.
- Allow force and position control with forces up to 100 lb and bandwidth up to 2 Hz
- Safely interact with the subject
- Affordability

We chose pneumatic cylinders to actuate the device because they provide high force levels, and yet are relatively affordable (less than $1000 per DOF, including cylinder, pressure and position sensors, servo and safety valves). In addition, when the cylinders are vented, they have excellent backdriveability. When the cylinders are pressurized, nonlinear control laws have been developed [9] that allow force- and position control with a bandwidth of at least 5 Hz, which is sufficient to control human pelvic motion.

B. Mechanical Design

Based on these design criteria, we have developed a device called the Pelvic Assist Manipulator (PAM) (Fig. 1). PAM consists of two, three DOF pneumatic robots that attach to the back of an adjustable belt worn by the subject. For each robot, the three pneumatic cylinders are anchored to a support pillar via ball-joints, and attach to a point through their lines of center to a revolute joint on the belt. Two cylinders lie coplanar in the horizontal plane, and the third cylinder lies in an oblique plane to provide upward forces. The resulting system has five DOF, providing control of three translations (side-to-side, forward-and-back, up-and-down) and two rotations (pelvic rotation about the Z-axis, and pelvic obliquity about the Y axis, Fig. 1). One rotation cannot be controlled – pelvic tilt about the X-axis. As shown schematically in Fig. 1, a separate, pneumatic over-head BWS mechanism partially unloads the patient's weight depending on the desired level of support. Each three-cylinder robot is mounted to an adjustable slide that allows the robots to be moved vertically to accommodate subjects of various hip heights. The mounting of the pneumatic cylinders on ball joints minimizes the moments that can be imparted onto the pistons, potentially damaging the cylinders. The cylinders attach to the belt behind the subject in order to allow for the subject to swing the arm naturally during gait and also to provide an unobstructed view for the subject. The cylinders are also angled in from the sides with sufficient spacing to allow the subject to enter the device via a wheelchair, and to allow the therapist to access the subject from both behind and on the sides, as is necessary for manual assistance of pelvic motion using a "teach-and-replay" strategy.

C. Control Design

To record movements, PAM's cylinders can be vented and the device can be used in a passive mode. The cylinders are instrumented with linear potentiometers. The position and orientation of the pelvis can be inferred in real-time from the potentiometer voltage measurements using the forward kinematics of the mechanism.

To replay desired movements, a hierarchical control system is used for which the actuator dynamics are separated from the rigid body dynamics of the robot (Fig. 2) [9]. This permits well-established control laws, like those used for motor driven robots, to be used for the pneumatic system. To achieve this hierarchy, we model and control the nonlinear compressible air flow dynamics for each cylinder and servovalve, and use pressure sensors on both sides of the pistons for feedback in order to achieve fast and accurate force control for each cylinder of the system. This transforms the control problem into one that is standard for robotic control designers. The inner-loop force control law is:

$$u = \left[-k_p \left(P_1 A_1 - P_2 A_2 - P_0 A_0 - F_d \right) + k_v \left(\frac{P_1 \dot{V}_1 A_1}{V_1} - \frac{P_2 \dot{V}_2 A_2}{V_2} \right) \right] k_g(x) \qquad (1)$$

k_p – governs response time of the force control subsystem
k_v – governs feed-forward control due to piston motion
P_1, P_2 – absolute pressures on each side of the piston
A_1, A_2 – areas on each side of the piston
P_0 – atmospheric pressure
A_0 – cross-sectional area of the rod
F_d – desired force
V_1, V_2 – volumes on each side of the piston
$k_g(x)$ – nonlinear loop gain

$$k_g(x) = \frac{V_1 V_2}{A_1 V_2 + A_2 V_1}$$

u – voltage control signal into proportional servo valve

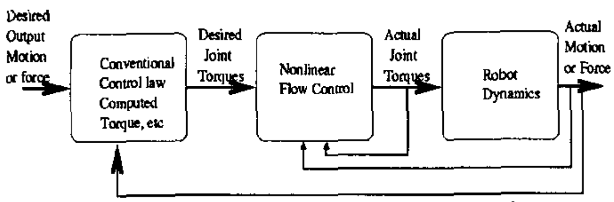


Fig. 2: Hierarchical, Nonlinear, Pneumatic Control Law

This control approach has been tested previously on UCI's three degree of freedom pneumatic robot [9]. In one experiment, the bandwidth of the force control algorithm was calculated to be approximately 5 Hz, ample for controlling even brisk human movement. In another experiment, the position-controlled robot, which was slightly larger than a human arm, moved along a trajectory programmed to pass through five extreme positions across the robot's workspace in a six second period with an average joint trajectory error less than 2 degrees.

D. Safety

Our approach toward the overriding concern of safety is to incorporate redundant mechanical, electrical, and software safety features. Pressure-actuated safety valves vent both sides of the cylinder, should the main supply pressure be cut, leaving the system in its passive state. Main supply pressure is vented with an electrically controlled valve when an emergency stop button is pressed. Main supply pressure is also vented when software limits on position, velocity, and pressure are exceeded.

III. RESULTS

PAM currently uses six 1.5" diameter pneumatic cylinders with a 12" stroke length (Bimba, Inc.). Each of PAM's three-cylinder robots can generate approximately 350 lbs. of force in the x-direction, 200 lbs. in the y-direction, and 140 lbs. in the z-direction at a 100 PSI supply pressure. The positions of the cylinder rods are measured by an analog voltage signal from the potentiometers that are integral within the cylinders. Pressures on each side of each cylinder are measured using low-cost pressure sensors (SenSym ICT). Air supply to, and exhaust from the cylinders is regulated by servovalves (Festo, Inc.). The system is controlled using Matlab xPC target.

PAM's cylinder lengths were chosen to accommodate normative and even moderately exaggerated hip movements should they be necessary (Fig. 3). At normal walking speeds, translational pelvic displacements are approximately 5 cm (~2 in.) up-and-down and 5 cm side-to-side; and normal angular pelvic displacements are approximately ±6° rotation and ±6° obliquity [5].

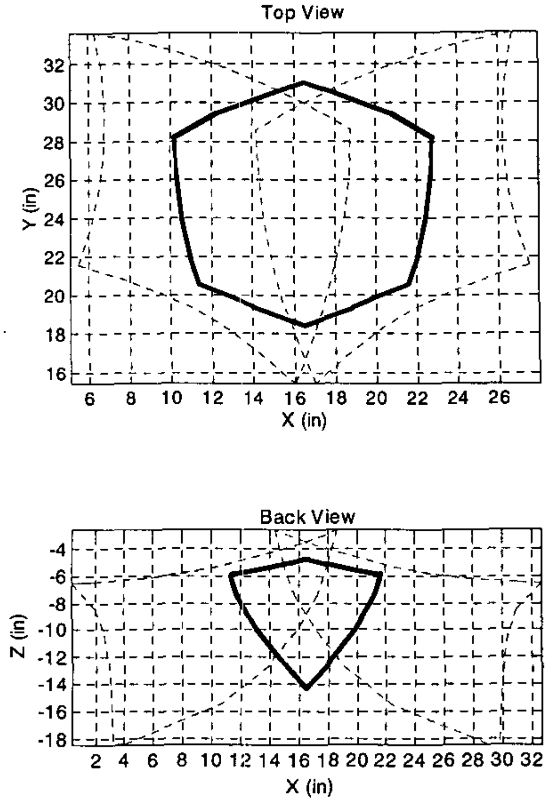
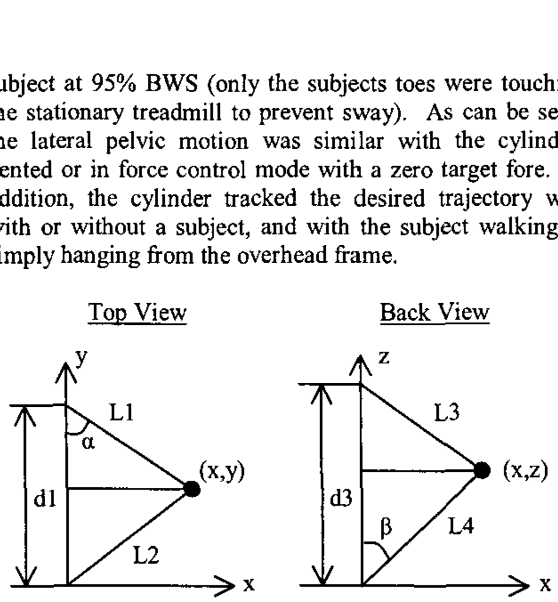


Fig. 3 PAM workspace. Dotted lines: Individual, uncoupled robot workspaces of left and right belt attachment points; Solid line: Workspace of the belt center-point that will allow ±6° of planar angular displacement, i.e. during normal walking speeds, of the belt in the assembled system (max belt angular displacement is about ±20°). Coordinate frame shown in Fig. 1 originating at the ball-joint of the posterior, horizontal cylinder.

To demonstrate PAM's ability to act as a passive motion capture and replay device and to validate our force control law, we collected lateral displacement (1 DOF) position voltage signals via the potentiometers in the pneumatic cylinders while an unimpaired subject walked over a treadmill moving at a constant speed (2 mph) (Fig. 5A). Motion capture was also taken by setting the desired force in our control law equal to zero and performing the same test. Forward kinematic equations (Fig. 4) were used to infer the position of the subject's hips throughout the stepping. From the raw data the averaged hip trajectory over all steps was calculated. We then used the calculated average from the passive motion capture as a desired replay trajectory. Fig. 5B plots the position tracking of this desired trajectory for three separate cases along with the desired trajectory and the average trajectory from the zero-desired-force motion capture trial. The first case is with the subject walking normally at 0% BWS, the second case is without a subject in the belt, and the third case is with a subject at 95% BWS (only the subjects toes were touching the stationary treadmill to prevent sway). As can be seen, the lateral pelvic motion was similar with the cylinders vented or in force control mode with a zero target fore. In addition, the cylinder tracked the desired trajectory well with or without a subject, and with the subject walking or simply hanging from the overhead frame.



$$\cos\alpha = \frac{L1^2 + d1^2 - L2^2}{2L1d1} \qquad \cos\beta = \frac{L4^2 + d3^2 - L3^2}{2L4d3}$$

$$x = L1\sin\alpha \qquad z = L4\sin\beta$$

$$y = L1\cos\alpha$$

Fig. 4. Forward kinematic equations to infer the position of the cylinders to belt attachment point (x, y, z).

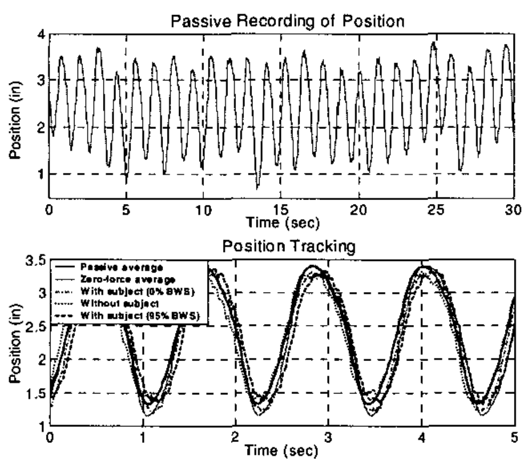


Fig. 5. A: Passive motion capture data of a subject's lateral hip displacement over a 30-second interval on a treadmill moving at 2 mph. B: Position tracking of the calculated average step trajectory from the data in Fig. 5A for three cases, along with that average of the passive motion capture data and also the average of a zero-force control motion capture data over a 5-second interval. Subject was a 23-year-old, 200 lbs., unimpaired male. Supply pressure was 85 psi.

IV. DISCUSSION/CONCLUSION

Robots have the potential to provide accessible, precise, and extended rehabilitation therapy, without the force limitations and inconsistency of conventional human-regulated therapy. By providing measurement and control over naturalistic pelvic motion, the robotic device described in this paper has the potential to offer an improved level of control over current locomotor training methods, both manual and robotic. The use of pneumatic actuators offers high force output, good backdriveablity, and good position and force control, at a relatively low cost.

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