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An Assistive Robotic Device That Can Synchronize To The Pelvic Motion During Human Gait Training

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Abstract— **We are developing a robotic device, PAM (Pelvic Assist Manipulator), that assists the pelvic motion during human gait training on a treadmill. PAM allows naturalistic motion of pelvis actuated by six pneumatic cylinders, which, combined with a nonlinear force-tracking controller, provide backdrivability and large force output at a relatively low cost. PAM can act as a teach-and-replay device with a PD position controller driving the pelvis onto the reference trajectory specified with or without the help of therapists. During initial experiments with unimpaired subjects, we encountered a problem in which the subjects had difficulty synchronizing their movements with the gait pattern reproduced by PAM, even though that gait pattern had been sampled from the subjects themselves. We introduced footswitches to detect the gait timing and developed a feedback control algorithm that adjusts the play-back speed of the gait pattern in real-time. The feedback algorithm is presented, along with data that shows the effectiveness of the algorithm in synchronizing the robotic assistance during stepping by unimpaired subjects, even when the subjects change their step size and period.**

I. INTRODUCTION

Gait training on a treadmill with body weight support (BWS) and manual assistance of the legs and pelvis is a promising new therapy method for people who lost their ability to walk after stroke or spinal cord injury [1]. However, BWS gait training is labor intensive, requiring a team of four therapists, with two therapists to guide the legs, one to support the pelvis and one to operate the treadmill and BWS system. In an attempt to reduce the physical load on the therapists and further improve the effectiveness and accessibility of gait training, robotic devices are being developed [2]. The Mechanized Gait Trainer [3], the Lokomat [4] and ARTHuR [5] are devices developed to assist primarily in leg motion. The String-Man utilizes a tension controlled wire-drive system and stabilizes the torso of a subject during stepping on a treadmill [6].

We are developing a pneumatic robotic device, called PAM (Pelvic Assist Manipulator), that can measure and manipulate naturalistic pelvic motion during BWS gait training on a treadmill. PAM is designed to take the place of the therapist who stands behind the subject and assist the motion of the pelvis. Previously, we developed a nonlinear controller to achieve force tracking with the pneumatic actuators, including backdrivability (i.e. zero force control), and constructed a PD position controller to demonstrate PAM's ability as a teach-and-replay device [7]. However, during initial experiments with unimpaired subjects, we encountered a fundamental problem. When PAM was position-controlled onto the repeating pattern of the mean pelvic trajectory, the subject could not maintain stable stepping more than several seconds at a time, going out of sync. In this paper, we explain this synchronization problem and describe an algorithm that we developed in order to solve the problem.

II. THE PELVIC ASSIST MANIPULATOR

A. Hardware

PAM consists of a pair of three degree-of-freedom (DOF) pneumatic robots that attach to the back of a belt worn by subject (Fig. 1). Each sub-robot has a tripod configuration with three pneumatic cylinders, whose axes intersect at a point through a custom-designed joint structure. A pair of those joints are connected to the belt piece via a universal joint mechanism whose axes also intersect at the same points. PAM holds 5 actuated DOF (3 translations and 2 rotations), and the remaining passive DOF (pelvic tilt) is not measured or controlled. A separate overhead BWS system unloads the subject. This configuration allows naturalistic motion of the pelvis while maintaining accessibility for the therapists and the patient's entry. PAM is back-drivable and compliant, yet capable of producing large forces at a relatively low cost of $1000 per DOF. It can generate roughly 150 lbs in the horizontal plane and 75 lbs vertical at a 40-50 PSI supply pressure. The translational workspace is fairly limited by the stroke lengths of the cylinders (roughly 10x10 inch in horizontal plane and 8 inch vertical) [7]. There is an additional hard-stop structure to mechanically prohibit extreme rotations. The hardstop, hanging from the overhead frame like a pendulum, can swing and vary its length to accommodate the full translation range, while limiting the angular motions typically within $\pm 40^\circ$ (pelvic rotation) and $\pm 15^\circ$ (obliquity). We developed a pair of custom footswitches to detect loading on the feet. The probes, consisting of Force Sensitive Resistors and supporting rubber material inserted under the heel in the shoes, are connected to the control PC through an interface circuit that gives digital signals (Loaded or Unloaded) by applying adjustable threshold detection.

B. Software

We adopted the hierarchical control strategy that was successfully applied to pneumatic actuators by McDonell [8]. We use Matlab Simulink and xPC to implement the real-time control task at a sampling rate of 500 Hz.

1) Force Tracking Controller: At the lower level of the hierarchy, we model the air flow and pressure dynamics for each chamber of the pneumatic cylinders, and achieve force tracking by canceling the nonlinear term in the model with pressure and position sensor feedback [9].

2) Position Controller: We constructed a PD position control law on top of the force tracking controller. The desired control forces and moments in task space are kinematically solved into desired cylinder forces $\mathbf{f}_d$, then passed down to the force tracking controller.

$$\mathbf{f}_d = \mathbf{J}^T\{\mathbf{G}_P(\mathbf{x} - \mathbf{x}_d) + \mathbf{G}_D(\mathbf{x} - \mathbf{x}_d)\} \qquad (1)$$

where $\mathbf{x}$ and $\mathbf{x}_d$ are the actual and desired position of the attachment belt respectively, and the Jacobian matrix $\mathbf{J}^T$ relates task space to joint space. We currently do not use a feed-forward term or computed-torque type term, although this approach is possible. The PD gain matrices, $\mathbf{G}_P$ and $\mathbf{G}_D$, are diagonal.

III. TEACH-AND-REPLAY

We record the pelvic trajectory during stepping with PAM in backdrive-mode, then compute a mean trajectory pattern by identifying step cycles and taking an average over them. We then replay the repeating sequence of the mean trajectory using the position controller. We wish to simulate a common situation in gait training where no or minimum assistance is given by therapists as long as subject is closely following the desired trajectory, but more assistance is provided "as needed" if he begins to deviate. After successfully testing replay against a 100-lbs punching bag [9], we proceeded to a second set of experiments in which the mean trajectory was replayed against the same unimpaired subject from whom the trajectory was sampled.

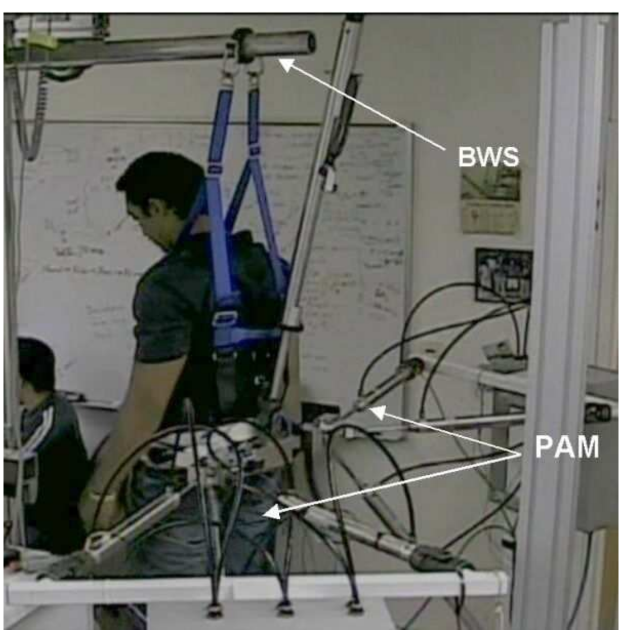

Fig. 1. PAM: The Pelvic Assist Manipulator

A problem emerged immediately. Subjects were not able to maintain stable stepping while PAM was replaying the gait pattern. What appeared to happen during the experiments was that the subject at first tried to feel the pattern of force that PAM was generating and adjust his step period and width accordingly, achieving synchronization eventually. Once synchronized, however, he lost the sensation of force acting on him, which he needed for the adjustment. While PAM replays the gait pattern at an exact constant period, it is very natural for a human subject to have some fluctuation in the step timing even when he is walking stably at a constant treadmill speed. Given the compliant nature of PAM, the fluctuation apparently led to de-synchronization. By the time the subject began to feel corrective forces clearly as a result of the growing tracking error, he was completely out of sync. PAM and the subject never stayed synchronized more than several seconds at a time.

If we measure the timing of each step, we speculated, then we could probably make PAM follow the pace of the subject properly. Indeed, human therapists utilize timing feedback (both vision and touch) to find which gait phase the subject is in. PAM, however, lacks the visual and tactile senses that therapists possess. It is difficult to find gait phase solely through the measurement of pelvic position because the motion is relatively small and not as clearly correlated to gait phase as the motion of the legs and feet. So, we introduced footswitches to detect the step timing, and developed a feedback control algorithm to adjust the replay timing.

IV. SYNCHRONIZATION ALGORITHM

The step timing measured by the footswitch contains two key pieces of information, period and phase. Our objective is to match these two parameters of PAM and the subject.

A. Period Feedback

The repeating sequence of the desired pelvic trajectory is generated by accessing and interpolating the mean trajectory data stored in Simulink's look-up table block (Fig. 2). An integrator block, with lower and upper saturations set to 0 and 1, implements a variable-speed timer that feeds normalized time index into the look-up table. The input to the integrator block, which determines timer speed, is adjusted depending on the detected step period (frequency). If the input to the integrator is constant at $1/T_0$, where T_0 is the period of the original mean trajectory, the timer advances at "normal speed." Once the timer saturates, an external trigger resets the integrator to 0. The actual step period can be found by measuring the elapsed time between the loading of one foot in two consecutive steps. We accomplish this by detecting the rising edges of footswitch signal. Given the period measurement, we apply the following feedback law.

$$f = f_0 + K(f_0 - f_{fs}) \qquad (2)$$

where f is the input to the integrator, $f_0 = 1/T_0$ is the frequency of the original mean step trajectory, $K < 0$ is the feedback gain, and $f_{fs} = 1/T_{fs}$ is the frequency detected

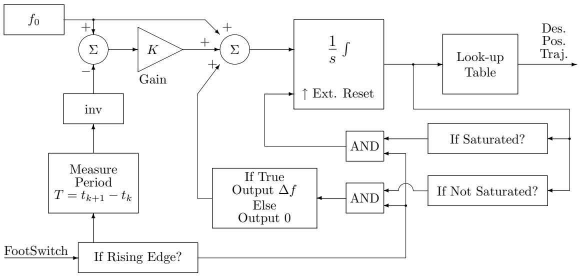

Fig. 2. Diagram of Synchronization Algorithm

by footswitch. The feedback algorithm changes the playback speed of the next cycle according to the last step period(s). If $K = -1$, for instance, then $f = f_{fs}$ and the playback speed is adjusted to compensate exactly for the mismatch of the most recently recorded step period with the previously recorded mean step period.

B. Phase Feedback

The period feedback law (Eq. 2) matches the periods of the gait patterns, but they could still be out of phase. In fact, if the periods are perfectly matched, whatever phase error there is would stay there. Now, the other major information obtained by the footswitch is the phase, which is the time at which the loading occurs (rising edge). We utilize this information to eliminate the phase error, more specifically phase lead and lag. For the lead, where PAM is replaying ahead of the subject, the algorithm holds the resetting of the timer momentarily, waiting for the subject to catch up. For the lag, where PAM is replaying behind the subject, the algorithm increases the playback speed by a constant f so that PAM can catch up with the subject. The complete algorithm is summarized in Fig. 2, from which we omitted some logic and saturation blocks that we have in the actual implementation mainly for safety purpose.

Adjusting playback speed in real-time can cause discontinuity in the desired velocity trajectory. In an extreme situation where the errors are large, the discontinuity may cause instability particularly with larger PD position gains. Under normal conditions, however, where the errors are reasonably small, the compliant nature of PAM allows smooth velocity transition, and the subject can continue to walk stably. In the following section, we present the data showing the effectiveness of the developed algorithm.

V. RESULTS

In Fig. 3, the timing chart during teach-and-replay with an unimpaired subject shows the synchronization performance when neither period nor phase feedback is utilized (top row), when only period feedback is used (row 2), when only phase feedback is turned on (row 3), and when both period and phase feedback are engaged (bottom row). The solid lines are the right footswitch signal, where High (1) represents loading, and Low (0) unloading. The dashed lines represent the normalized time index output of the variable-speed timer, showing a saw tooth-like profile as the timer counts up and

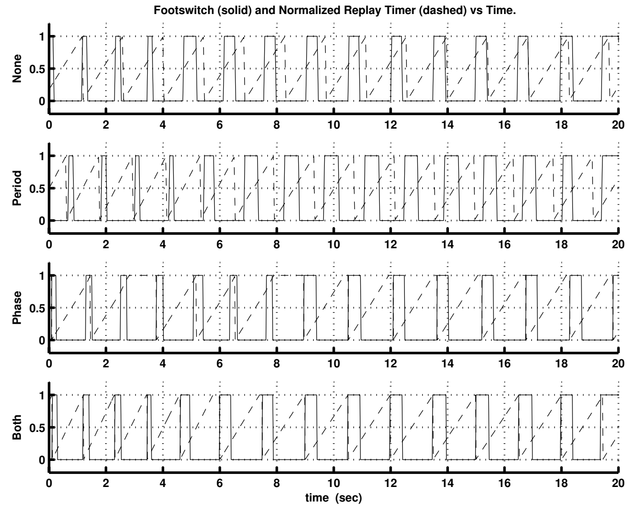

Fig. 3. Playback Timer and Footswitch Signal during Teach-and-Replay.

resets repeatedly. Synchronization of the robot and subject can be judged as follows: if the falling edge of the timer signal is matched to the rising edge of footswitch signal, then the robot and subject were synchronized. For the data shown, the subject intentionally changed step size (and thus period) from shorter to longer at around t=5, while the treadmill remained at 2 MPH. The gain parameters were set to $K = -1$ and $f = 0.1$.

In the case without the synchronization algorithm ("None" in Fig. 3), the playback timer repeated with a constant period of T_0 regardless of the footswitch signal. The rising edge of the footswitch and the falling edge of the timer typically did not match, and thus the robot and subject were rarely synchronized. The subject's perception was that the robot randomly disturbed his gait. For the next case in which only "Period" feedback was implemented, the periods matched, but the phase error remained. After the transition from shorter to longer steps, the phases were almost completely opposite to each other, making the subject feel as if he was walking with a spring that pushed against him in every direction he moved. In the "Phase" feedback case, the playback speed (slope of the saw tooth) remained constant, but the resetting of the timer was paused, for example at t=3 and t=8. This resulted in a skipped cycle for a few shorter steps taken by the subject, or persistent short pausing for the longer steps ($t > 10$). Lastly, when "Both" period and phase are adjusted, the falling and rising edges matched closely for every step. The pausing required to maintain appropriate phasing was very small. In this case, synchronization was sustained, and the subject walked smoothly and comfortably as PAM followed closely after his gait motion.

Fig. 4 shows mean and standard deviation of the period and phase errors during replay for 3 unimpaired male subjects as well as the total power output by PAM, computed by multiplying force and velocity for all cylinders. During the experiment, the subjects were asked to change their step size deliberately with the following sequence: (normal - wide - short - wide - normal - short - normal), with 10 steps for

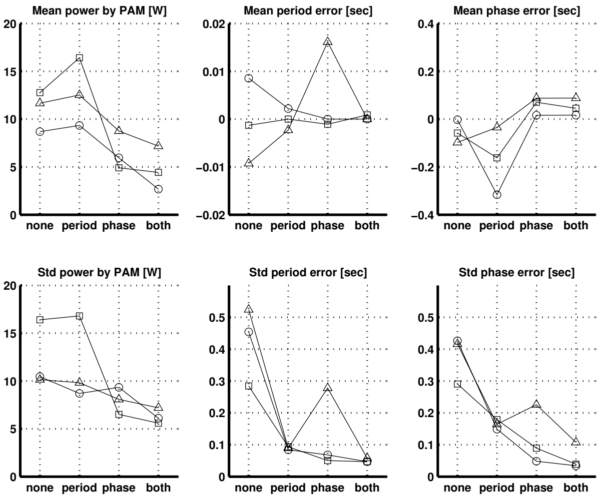

Fig. 4. Mean and Standard Deviation of Timing Errors and Power Output by PAM during Teach-and-Replay for 3 unimpaired subjects.

each. The period and phase errors were consistently small for all subjects when "Both" period and phase feedback were engaged, and they were larger when "None" was used, consistent with the findings from Fig. 3. Another key finding was that, when the synchronization algorithm was not utilized and thus PAM was out of sync, PAM generated substantially larger power across all subjects, indicating that it was "fighting" the subject. We would like to highlight that this data was taken as the subjects dramatically changed their step size and period. The synchronization algorithm compensated for these variations such that the subjects felt as if the robot was moving along with them, not fighting or perturbing them.

VI. CONCLUSIONS AND FUTURE WORKS

When a subject is too weak to initiate or maintain stable stepping by himself, human therapists would dictate the gait timing, assisting the legs and pelvis almost fully. When a subject can stably walk all by himself, there would be no need for assistance by therapists or robots. Now, rehabilitation occurs predominately somewhere between these full-assist and no-assist situations. An experienced therapist would let the subject take the initiative as much as possible, providing "just enough" assistance to maintain stable stepping. However, this is a challenging task for a robot because the control objective is not clear, residing somewhere between rigorous position tracking and complete backdrivability. For an effective training, therefore, a therapist, or a robot, must 1) make some measurement of the free system, which is the subject trying to make steps, 2) evaluate what and how much assistance is desired, and 3) actually apply the desired pattern of force. In other words, they must be able to intelligently switch between a "sensor-mode" and a "power-mode". We are essentially developing a robot that tries to disappear ultimately. This may seem a contradiction, but we think such a robot is desirable for rehabilitation. As a step toward that goal, we believe it is crucial for the robot to synchronize to the gait timing of the subject in real-time. Based on initial difficulties in synchronizing the robot assistance with unimpaired subjects' gait patterns, we developed an algorithm that is based on feedback derived from a footswitch signal. The algorithm achieves stable synchronization under the teach-and-replay scheme with unimpaired subjects, even when the subjects change step size and period.

We are currently arranging for initial experiments with impaired subjects. Recognizing that teach-and-replay as is may not work with them, we are prepared to approach the problem by modifying the desired trajectory, at first, in its amplitude and offset. We also plan on applying a position control law more sophisticated than a simple PD. Furthermore, we are currently developing a leg robot, called POGO (Pneumatically Operated Gait Orthosis), that is designed to attach to and work with PAM. Once POGO becomes operational and integrated, we could use it to find the gait phase instead of or in addition to the footswitches. It may even be possible to detect gait phase in a more continuous manner, as opposed to discretely (only at rising edges). If so, we envision actively manipulating the phasing in such a way that the robot "guide" the subject by staying ahead just enough.

VII. ACKNOWLEDGMENTS

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REFERENCES

[1] A. Behrman and S. Harkema, "Locomotor training after human spinal cord injury: a series of case studies," *Physical Therapy*, vol. 80, pp. 688–700, 2000.

[2] V. Edgerton, R. de Leon, S. Harkema, J. Hodgson, N. London, D. Reinkensmeyer, R. Roy, R. Talmadge, N. Tillakaratne, W. Timoszyk, and A. Tobin, "Retraining the injured spinal cord," *Journal of Physiology-London*, vol. 533, no. 1, pp. 15–22, May 2001.

[3] S. Hesse and D. Uhlenbrock, "A mechanized gait trainer for restoration of gait," *Journal of Rehabilitation Research and Development*, vol. 37, no. 6, pp. 701–708, Nov-Dec 2000.

[4] S. Jezernik, G. Colombo, T. Keller, H. Frueh, and M. Morari, "Robotic orthosis lokomat: A rehabilitation and research tool," *Neuromodulation*, vol. 6, no. 2, pp. 108–115, Apr 2003.

[5] D. Reinkensmeyer, J. Wynne, and S. Harkema, "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*, pp. 2353–2354, October 23-26 2002.

[6] D. Surdilovic and R. Bernhardt, "String-man: A novel wire robot for gait rehabilitation," *Proceedings of the 2004 IEEE International Conference on Robotics and Automation*, pp. 2031–2036, 2004.

[7] W. Ichinose, D. Reinkensmeyer, D. Aoyagi, J. Lin, K. Ngai, V. Edgerton, S. Harkema, and J. Bobrow, "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, 2003.

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

[9] D. Aoyagi, W. Ichinose, D. Reinkensmeyer, and J. Bobrow, "Human step rehabilitation using a robot attached to the pelvis," *Proceedings of the 2004 ASME International Mechanical Engineering Congress and Exposition*, 2004.