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A robotic stepper device concept for locomotion rehabilitation

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A novel strategy for rehabilitation of locomotion impaired subjects uses a Body Weight Support Technique (BWST) on a treadmill which involves three to four therapists to carry out the required patient training exercises on the treadmill. This paper briefly describes (i) the essence of the novel rehabilitation strategy, including its medical background, (ii) the technical approach to the design and development of a robotic device aimed to reduce the manual involvement of at least two therapists in the locomotion training exercises on a treadmill, and (iii) the main conceptual design features of a possible robotic device.

Key words: biped locomotion, rehabilitation, treadmill, force-torque sensing, human-machine interaction and interface

1. Introduction

Many tens of thousands of people are hospitalized in the USA each year due to head or central nervous system injuries or diseases. Most of them are stroke or spinal cord injury patients. These injuries result in partial or total paralysis. Some patients will retain life-long impairment, but a significant percentage (about 70%) of the patients could be retrained to walk since medical experiments suggest that a significant degree of functional neural regeneration can be achieved by consistent proper practice and training. More on the related medical research background can be found in Refs. 1-3.

A specific current training technique for rehabilitation of stepping skills uses a Body Weight Support Technique (BWST) on a treadmill. In this training practice, physical therapists manually assist the legs of locomotion impaired patients during stepping exercises on the treadmill, while the bodyweight of the patient is partially supported by a harness attached to an overhead lift. This type of locomotion training requires three to four specifically trained therapists. Two therapists hold the legs, one for each leg, with two hands. They hold the legs distal to the patella to assist with knee extension during

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stance, and just above the ankle to assist with swing and foot clearance. A third therapist stabilizes the pelvis, and a fourth handles the overall mechanical and motoric setting. The goal of the therapists is to help provide the patient with appropriate kinetics and kinematics of stepping driven by the motion of the treadmill. With appropriate input from therapists, this approach can be used to efficiently reduce gait deviations of the patients on a treadmill. It is hypothesized that this training technique permits the neural networks of the brainstem and spinal cord to receive more normal step-related sensory feedback after neurologic injury.

The current practice of BWST training has important scientific, functional and economic limitations. First, the therapists who assist the leg only can provide a crude estimate of the required force, torque and acceleration necessary for stepping. To date all studies of step training using BWST have been limited by an inability to quantify the kinetics and kinematics acting at the joints of the lower limbs. According to medical opinion, this information seems critical to fully assess the changes that might be attributable to BWST step training on a treadmill. Second, the movements of the manually manipulated limbs only approximate but do not replicate the normal kinematics and kinetics of the human legs during stepping, and the patient’s ability to step properly seems highly dependent upon the skill level of the persons conducting the training. Third, the human resources needed to conduct patient training with BWST on a treadmill are considerable and limit its use to a vary narrow community of patients.

The above limitations of the currently used manual procedures motivated the idea to develop a Programmable Stepper Device (PSD) as a *robotic aid* that can (i) measure and interpret feedback about forces, torques and accelerations exerted by a patient’s lower extremity during BWST stepping on a treadmill, (ii) assist the completion of a step in a precise and repeatable manner, and (iii) accommodate a variety of treadmill speeds and individual step kinematics and kinetics. The idea of a robotic PSD can be considered as a needed general purpose scientific tool, as well as a first step to gain technical insight into the construction of a cost-effective and practical clinical and therapeutic device suited to fit the needs of a broad user community. *The PSD is intended to standardize the rehabilitation training and reduce the number of therapists needed to administer it.*

The subsequent part of this paper will (i) outline the technical approach selected to the design and development of a PSD and (ii) describe the conceptual design features of the PSD under consideration.

2. Technical Approach

The selected technical approach to a successful PSD design and development is based on two elements: (i) the acquisition of a strong scientific and engineering database for step kinematics and dynamics on a treadmill *as measured through the hands of a therapist assisting various patients during BWST training exercises* and (ii) a broad set of *virtual and physical tests on selected PSD design concepts* to verify hypotheses on anticipated results and efficiency. (Here, "virtual test" signifies model-based computer graphics simulation of procedure and performance.)

Two measurement systems were developed to measure a therapist's two-handed kinematic and dynamic interaction with a patients leg during BWST training on a treadmill. The first uses a force-torque sensor system, the second uses a combined force-torque and acceleration sensor system.

A. - The force-torque sensor based two-hand measurement system set-up is shown in Figure 1. Figure 2 shows an initial placement of the two sensors on a patient's leg. Note that the padded mechanical elements are firmly attached to the patient's leg at the indicated two places. Note also that the mechanical elements fitted to the therapists right and left hands permit a convenient firm grasp and hold of the measurement system without direct manual contact or touch of the patients leg. This assures that all forces and torques between the therapist's hand and the patients leg will go through the sensors during locomotion training using BWST on a treadmill.

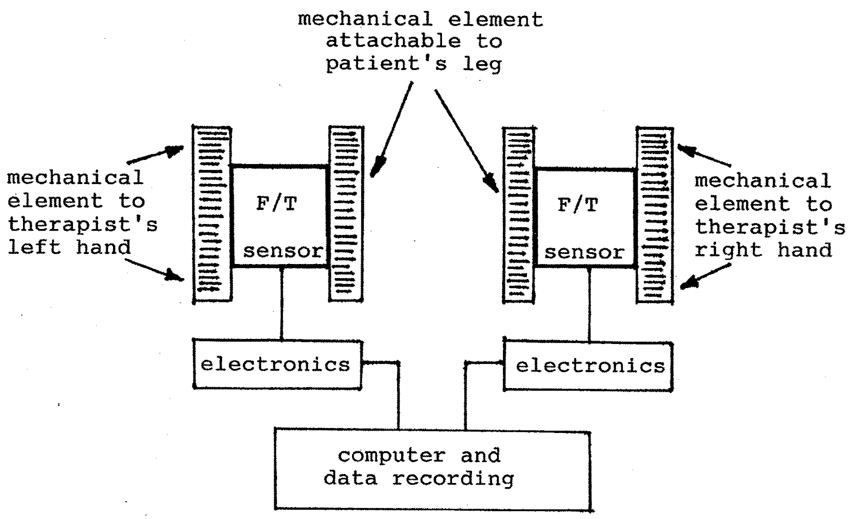

Figure 1. Two-hand force torque (F/T) measurement system

Each sensor is a six-dimensional vector sensor, measuring the three orthogonal forces and three orthogonal torques at the point of interaction between the therapist's hand and the patient's leg. The reference frame of the sensors is a Cartesian frame as indicated in Figure 2. The sensor system applied in this rehabilitation research is a commercialized version of the original sensor system transferred by JPL to industry in the mid 1980's. (See Ref. 4.) The physical dimensions of the applied sensor are shown in Figure 3 in millimeters. The sensor is called "mini-sensor" because of its dimensions and dynamic range. The dynamic range of this mini-sensor is: Fx and Fy $\pm$10 lb with 0.15 oz resolution, Fz $\pm$30 lb, with 0.45 oz resolution, and Tx, Ty, Tz $\pm$20 in-lb, with

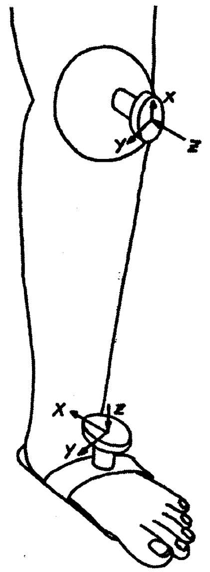

Figure 2. Placement of F/T sensors

0.15 in-lb resolution (for unit definitions in IS see Ref. 6). The sensors mechanical frame and reference frame are shown in Figure 4. As indicated on this Figure, the full sensor provides eight output readings (w1,. . . ,w8) from the semiconductor strain gages through eight electric full bridge arrangements. The amplifying and multiplexing electronics is located about 2 meters from the sensor heads and provide 1 KHz digital output readings.

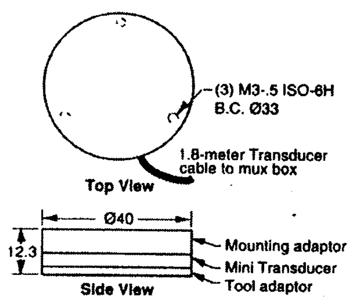

Figure 3. Dimensions of mini F/T sensors (in mm)

The functionality of the force-torque measurement system was first tested on a “simulated patient” assisted by a therapist at the patient’s knee. The measured results are shown in Figure 5 which should be read from the right to the left to see the “simulated improvements” in the patient’s walking behavior on the BWST treadmill through the

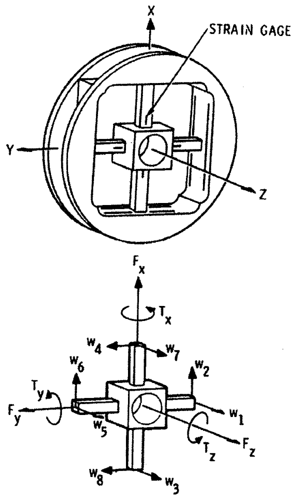

Figure 4. F/T sensors mechanical frame with output in cartesian frame

recorded force-torque assistance effort of the therapist. The comparison of the curves from the right to the left is self-explanatory for the improved walking behavior of the simulated patient.

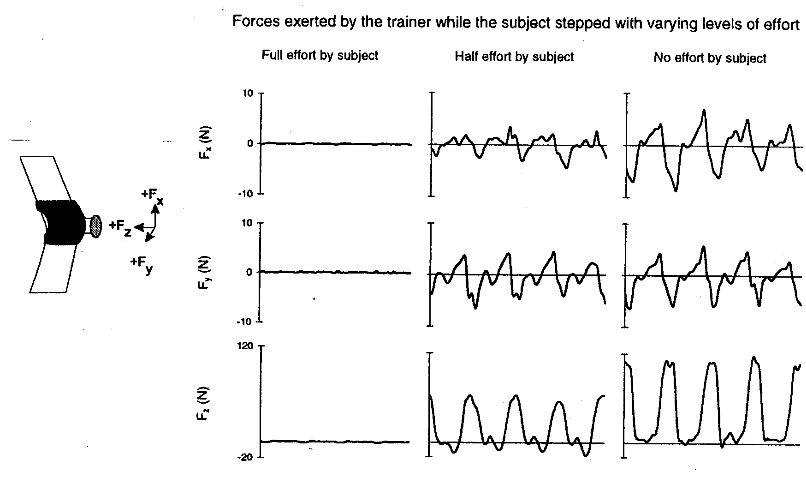

Figure 5. F/T sensors functionality test at knee

Several measurement cycles were also carried out on locomotion impaired patients to evaluate the utility of the installed two-hand force-torque sensor system. The results were very encouraging. As an illustration, a part of a case study is quoted in two figures. Figure

6 shows the actual case geometry, and Figure 7 shows a 10-second segment of the related graphically recorded data. A few notes are necessary about Figure 7. (i) The numbers on the horizontal axis denote seconds, and the numbers on the vertical axis denote lbs for force F and in-lbs for torque T. (ii) The 10-second stepping segment in Fig. 7 starts at the 10th second of the training exercise, because during the first 10 seconds the therapist was mostly occupied with placing the patient's leg properly over the treadmill. After the 20th second several more continuing 10-second segments also were recorded which displayed very nearly the same force-torque assistance pattern shown in Fig. 7. (iii) Only 8 parallel data sets could be printed out on the available recording equipment. Figure 7 shows the 8 most important data sets out of the measured 12 variables: 3 knee and 3 ankle forces and 2 knee torques.

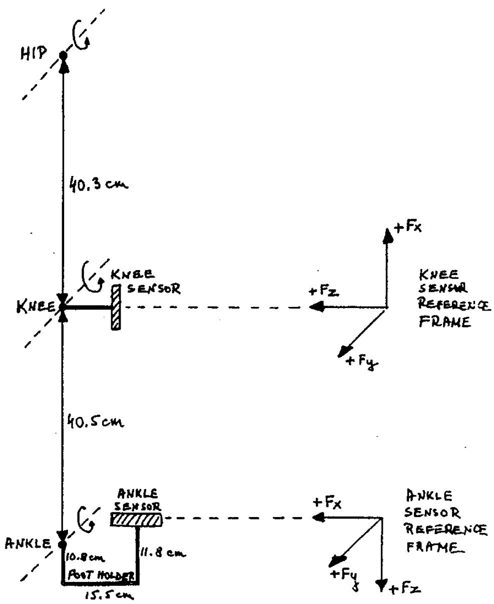

Figure 6. An application case geometry

It is noted that the data measured by the two-hand force-torque sensor system only tell about the therapist's effort as seen by the patient's leg motion on the treadmill, which is the real purpose and utility of this sensor system. But this sensor system can not measure the total torques acting at the patient's hip, knee and ankle joints, since the total torque at each joint is a vector sum of three torque vectors. Symbolically,

$$T(total) = T(voluntary) + T(treadmill) + T(therapist)$$

where $T(voluntary)$ denotes the amount of torque the patient can deliver (hopefully on an increasing level after more training), and $T(treadmill)$ denotes the torque origi-

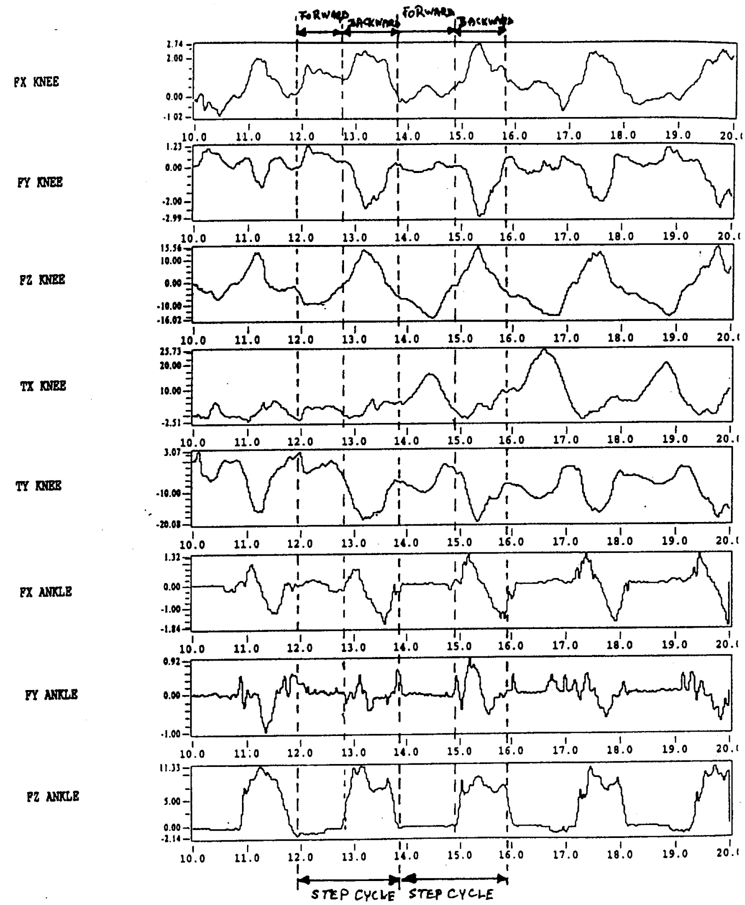

Figure 7. A 10-second recording data set during training of an acute SCI patient

nating from the patient's foot contact with the treadmill. A reasonable estimate, however, can be derived from Fig. 7 for torque values acting at the patient's hip, knee and ankle joints originating from the therapist's assistance, as follows.

In Figure 7 two step cycles are marked up sequentially between 11.9 - 13.9 and 13.9 - 15.9 seconds time segments, indicating also the "forward" and "backward" states of leg motion within each cycle. Assuming that the relative orientation of the two force-torque sensor axes as shown in Figure 6 remains constant during leg motion, the following force components can be treated as additive elements (of course, by taking account of their +/- signs):

$$Fx(knee) + Fz(ankle) = F(up - down) \quad (1)$$

$$Fz(knee) + Fx(ankle) = F(forward - backward) \quad (2)$$

$$Fy(knee) + Fy(ankle) \quad = \quad F(sideways) \tag{3}$$

where “up-down,” “forward-backward” and “sideways” denote orthogonal orientations relative to the treadmill belt. Based on the above approximate equations, the following approximate average force values delivered by the therapist hold during the first step cycle (that is, in the 11.9 - 13.9 seconds time segment):

F(up/forward)	1.8 lbs
F(forward)	9.0 lbs
F(sideways/forward)	1.0 lbs
F(down/backward)	8.0 lbs
F(backward)	8.0 lbs
F(sideways/backward)	1.0 lbs

From the above force values one may estimate about 31 in-lbs backward/forward (pitch) torque at the hip joint. The quite variable and sometimes quite high roll torque acting at the knee joint, Tx(knee), has a maximum value up to 28 in-lbs. Note, however, that the above quoted numerical values carry about $\pm$(20 to 25)% uncertainty due to the various assumptions used in their derivation. In particular, a more accurate calculation would require the use of the Jacobian matrices. That was omitted here because of the incomplete nature of the available data sets.

B. - Combined force-torque and acceleration measurement system was also implemented, motivated by the general engineering idea and experience that irregularities in the mechanical motion of a given solid body can be observed quicker and controlled better through acceleration measurements. For this sensing implementation a commercially available small robot sensor unit has been selected (see Reference 5) which in a single instrumentation package measures three orthogonal forces, three orthogonal torques, three orthogonal linear and three orthogonal angular accelerations. Thus, a single sensor unit produces twelve measurement outputs.

Figure 8 shows two combined force-torque and acceleration (F/T&A) sensor units attached to an experimental leg exoskeleton frame. One sensor unit is located at the knee element of the frame and another one at the lower circular frame element, which is slightly above the ankle. These are the same positions where a therapist normally guides the leg of a patient on a treadmill, using two hands.

The exoskeleton assembly (see Figure 9) consists of one half ring that attaches to the knee of the patient and two half rings that are mounted slightly above the patient’s ankle. The half ring at the knee is attached using two pivot points to a padded plastic kneecap that is mounted on the patient’s knee with Velcro straps. Through this mounting style the orientation of the upper F/T&A sensor is given by the bending angle of the lower leg which is known through potentiometers attached to the leg. The two half rings at the ankle are padded for comfort and connect to each other via adjusting screws allowing their distance to be changed to accommodate various patient dimensions. The knee and

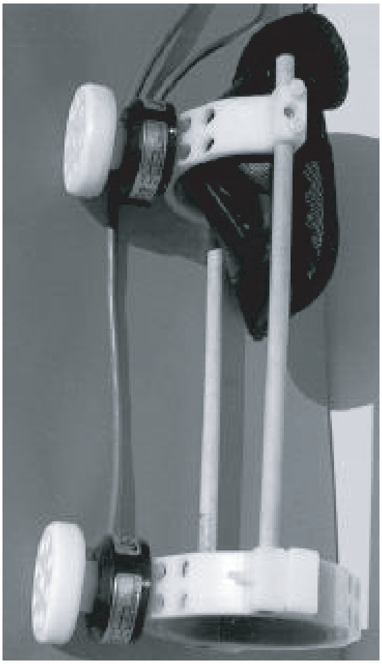

Figure 8. Leg exoskeleton frame equipped with two F/T/A sensors units. A kneecap is part of the frame.

ankle attachments are connected by two rods. The distance of the two attachments are adjustable by varying rod length to accommodate variations in the patients' lower leg length. The two F/T&A sensors are mounted to the forward pointing half rings. The sensors are equipped with appropriate handles so that a therapist can move a patient's leg without touching the leg and without the output end of the sensor. The cables coming out of each sensor are routed so that they do not interfere with the patient's leg motion.

The sensors interface to two DSP boards each. Thus, there is a need for four DSP cards for the two sensors. These cards are ISA standard. The controlling computer, therefore, has to have at least four empty ISA slots. The computer collects F/T&A sensor data into a file together with a time variable. In order to synchronize the time data with other computers, the data collection software outputs a pulse on the serial port at time zero. The data collection software consists of two parts. One is a low level software in assembly language that is executed by a hardware clock every 1 msec. It performs housekeeping of the four DSP cards and reading the F/T&A sensor data from the DSP into the memory of the high level software. The high level software reads the data from the memory and displays them on a screen for visual diagnostics. It also writes the data into a data file with a time index.

Figure 10 shows the 24 variables measured by the two F/T&A sensor units in a horizontal bar graph format on a monitor. To the left of the vertical center line the values are negative, to the right positive. The numerical values associated with the graph bars

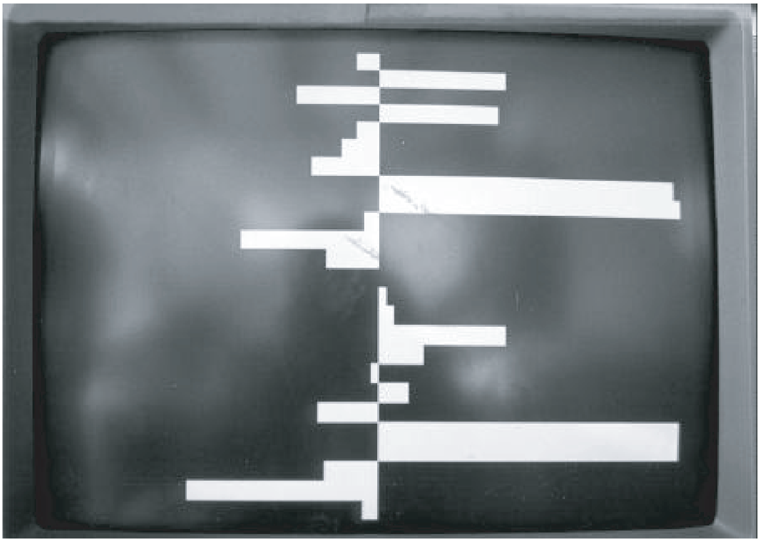

Figure 9. Bar graph display of measurement data of two F/T/A sensors units for engineering tests

can be scaled to selected maximum output values. The upper group of twelve bars on the screen is from the knee sensor unit, and the lower group of twelve bars is from the ankle sensor unit. The sequence of bars from top down in each twelve-bar group is as follows: XYZ forces, XYZ torques, XYZ linear and XYZ angular accelerations.

Figure 10. Sensor-equipped exoskeleton attached to a leg for fitting tests and adjustments. The lower ring to be patted against the leg.

The last work with this F/T&A sensor unit was focused at the following issues: (i) The therapist's manual interaction with the exoskeleton frame at the location of the two sensor units. (ii) The exoskeleton frame's interaction with the motion of variable size legs of different patients. (iii) Sensor data filtering and real-time data display formats.

(iv) Data recording and transfer to a time-integrated bank of simultaneously sensed other data related to the motion of a patient's leg on a treadmill.

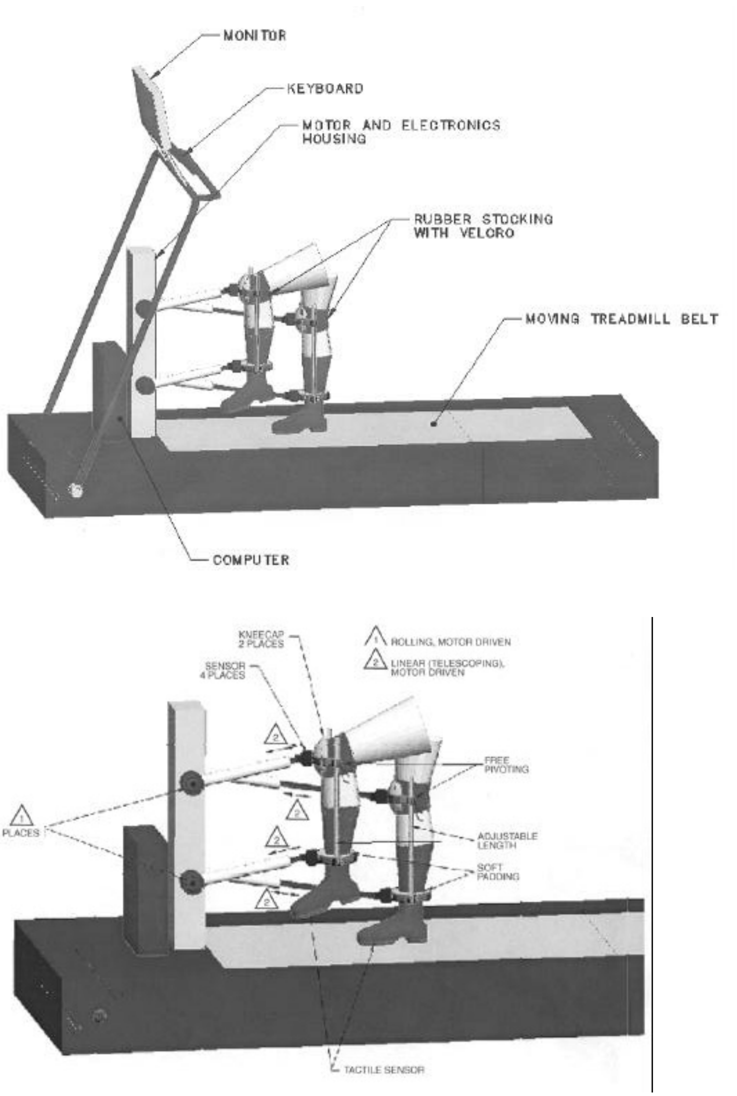

Figure 11. A possible PSD system architecture uses two two-degree-of-freedom robot arms acting in the sagittal plane and connected to an exoskeleton leg

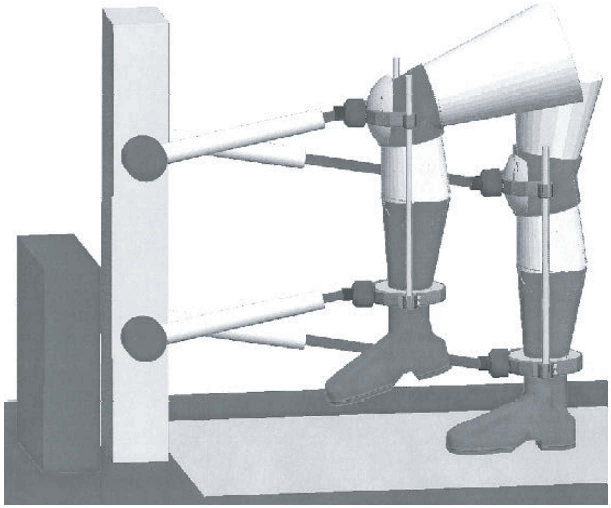

Figure 12. Close-up view of robot arms and exoskeleton legs

3. Engineering Concept Designs

Engineering concept designs of PSD as a robotic aid are being studied using computer graphics simulation of possible system architectures. A possible and quite plausible system architecture is based on the concept of replacing the therapist's two-hand action with two two-degree-of-freedom robot arms acting in the sagittal plane of leg motion and connected to an exoskeleton leg frame equipped with two F/T&A sensors as shown in Figure 11. This figure also indicates the envisioned major system elements and functional components. Figure 12 shows a close-up view of the sensor-equipped arms and exoskeleton leg arrangement over a treadmill. Figure 13 depicts the system arrangement in a full BWST setting indicating some of the major functional system elements. Figure 14 shows the full BWST-PSD system in two oblique views.

Computer graphics simulation studies on alternative system architecture concepts are also conducted. Active or passive robotic interaction with the patient's foot behavior over the treadmill is also considered. An alternative system design concept would be to use one three-degree-of-freedom robot arm connected to the exoskeleton leg frame so that the third degree-of-freedom would actively modulate the patient's foot behavior over the treadmill.

This paper is dedicated to the memory of Professor Adam Morecki who pioneered many works and efforts in robotics, including the robotic modeling of legged loc motion.

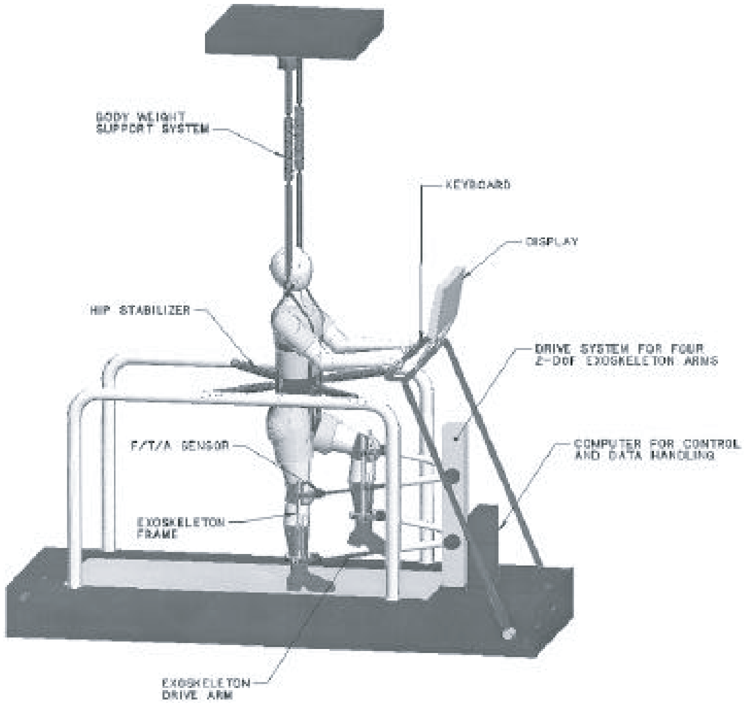

Figure 13. Full BWST arrangement with PSD, with major system elements indicated

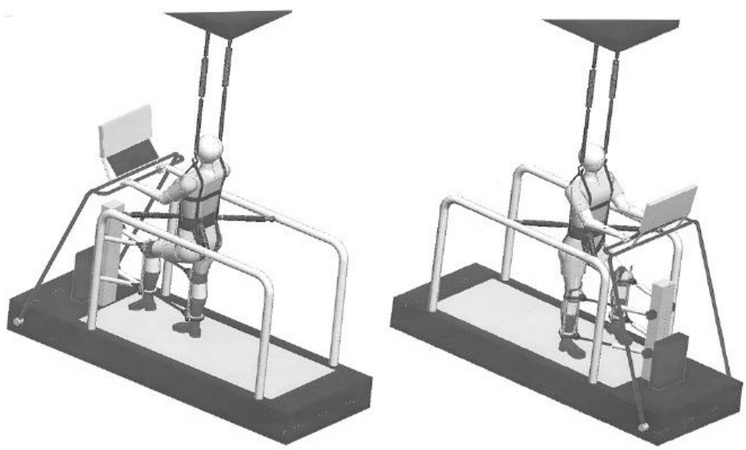

Figure 14. Full BWST arrangement with PSD in two oblique views

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[5] Combined force-torque-acceleration sensors from *JR3, Inc.*, Woodland, CA 96776, USA. Fax: 530-661-3701