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A Pneumatic Robot for Re-Training Arm Movement after Stroke: Rationale and Mechanical Design

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Abstract—This paper describes the development of a pneumatic robot for functional movement training of the arm and hand after stroke. The device is based on the Wilmington Robotic Exoskeleton (WREX), a passive, mobile arm support developed for children with arm weakness caused by a debilitative condition. Previously, we scaled WREX for use by adults, instrumented it with potentiometers, and incorporated a simple grip strength sensor. The resulting passive device (Training WREX or "T-WREX") allows individuals with severe motor impairment to practice functional movements (reaching, eating, and washing) in a simple virtual reality environment called Java Therapy 2.0. However, the device is limited since it can only apply a fixed pattern of assistive forces to the arm. In addition, its gravity balance function does not restore full range of motion. Therefore, we are also developing a robotic version of WREX named Pneu-WREX, which can apply a wide range of forces to the arm during naturalistic movements. Pneu-WREX uses pneumatic actuators, non-linear force control, and passive counter-balancing to allow application of a wide range of forces during naturalistic upper extremity movements. Besides a detailed description of the mechanical design and kinematics of Pneu-WREX, we present results from a survey of 29 therapists on the use of such a robotic device.

I. INTRODUCTION

Each year in the U.S. over 700,000 people survive a stroke [1]. Approximately 50% of stroke survivors have chronic hemiparesis [1]. Movement impairments are typically treated with intensive, hands-on physical and occupational therapy for several weeks after the initial injury. Unfortunately, due to economic pressures on the U.S. health care system, stroke patients are receiving less therapy. Consequently, the home rehabilitation that results from these pressures is self directed with little professional or quantitative feedback. Approximately 26% of chronic stroke survivors become dependent in activities of daily living [1].

A growing body of evidence suggests that both acute and chronic stroke survivors can improve movement ability with intensive, supervised training [2]. Thus, an important goal for rehabilitation engineering is to develop technology that allows the rapidly growing U.S. stroke population to practice intensive movement training without the expense of a continuously present therapist. This paper briefly reviews our recent development of a low-cost, passive orthosis for arm movement training after stroke. The paper then describes the rationale and initial development of a robotic orthosis for movement training, which is based on our experience with the passive orthosis.

A. *Java Therapy and T-WREX*

We developed Java Therapy [3] as a first-step toward home-based training. Java Therapy used a force feedback joystick to assist or resist in movements of the hand in a small workspace, and a web-based software system to remotely specify movement exercises and track progress. While very low-cost, Java Therapy's small workspace movements were not closely related to the types of functional movements which stroke survivors wished to improve, such as reaching, eating, dressing, and washing.

We therefore developed an improved input device for Java Therapy by modifying an anti-gravity arm orthosis, the Wilmington Robotic Exoskeleton (WREX). WREX was originally designed to help children with weakened arms to perform activities of daily living, such as eating [4]. WREX uses elastic bands, wrapped around two four bar mechanisms, to counterbalance the arm. WREX is a five degrees-of-freedom, backdriveable, passive device. It allows naturalistic movements across an estimated 66% of the normal workspace of the arm in the vertical plane and 72% in the horizontal plane. Thus, it is well suited for measuring functional arm movement. In addition, because it counterbalances the weight of the arm, it could potentially allow even a severely weakened stroke patient to practice functional arm movements at home, without the safety concerns raised by an active robotic device.

We adapted WREX for use in movement training by stroke patients in four ways, resulting in a device called T-WREX (for "Training WREX") (Fig 1) [5]. First, we made WREX larger, stronger, and simpler to manufacture. Second, we instrumented T-WREX with joint angle sensors

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(potentiometers), so that it could be used as a 3D computer input device. Third, we incorporated a simple, custom, hydraulic grip strength sensor into the handle. This sensor allowed both grasp and release motions to be sensed even in subjects with very minimal hand function. Finally, we created a Java Therapy 2.0 software system that had games for use with T-WREX. These simple, virtual-reality-like games were functionally oriented: reaching for items on shelves, washing a stove, eating, washing the contralateral arm, and picking up eggs and breaking them over a pan.

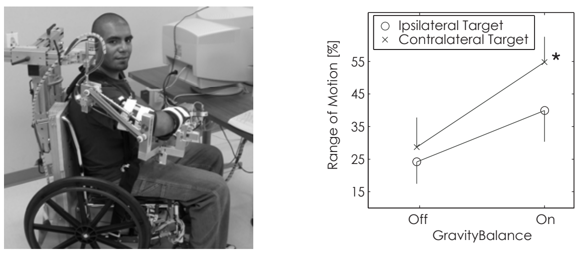

Figure 1: Left: T-WREX. Right: Average reaching range of motion across 9 chronic stroke subjects while using T-WREX, to targets with and with out gravity balance (distance traveled to target/total distance to target). $* \ p < .05$, paired t-test.

We are currently testing whether intensive practice by chronic stroke subjects with T-WREX transfers to functional recovery. Our subjective impression so far is that the subjects are highly motivated to practice the "cartoon-like" functional movements made possible by the combination of the gravity balance of T-WREX, the grip sensor, and the simple virtual reality interface of Java Therapy 2.0.

B. Rationale for a Robotic WREX

While T-WREX is promising as a home-based movement trainer because of its relatively low cost and inherent safety, it has several limitations. In a previously reported study [5], we quantified the ability of T-WREX to measure and assist in functional arm movements across a large workspace of the arm. T-WREX's gravity balance function improved a clinical measure of arm movement, range of motion of reaching movements, and accuracy of drawing movements while the device was worn. However, the gravity balance provided by T-WREX was not enough to restore full volitional range of motion (Fig 1) [5]. Subjects had particular difficulty in external rotation of the upper extremity, even though T-WREX allowed such movement. A possible explanation is that tone or position-dependent weakness limited the effectiveness of the passive counterbalance.

Another limitation of T-WREX is that it can only apply a fixed pattern of assistive force to the arm (i.e. the rubber-band-based pattern of gravity balance). Although adding and removing rubber bands varies the amount of gravity balance, it is impossible to apply dynamic patterns of assistive or resistive force. Recent research in robot-assisted movement training suggests that dynamic patterns of force may better enhance motor recovery [6-9].

We also surveyed rehabilitation therapists to determine if a robotic version of T-WREX was necessary. For this survey, we showed the therapists a video of a patient using T-WREX, explained its use and the gravity-balance function, and then explained that we intended to make a robotic version that could actively move the patient's joints.

We gave the survey to 29 practicing therapists (17 Physical Therapists and 12 Occupational Therapists) from 9 rehabilitation facilities. When asked if they believed that the robotic properties of the active orthosis were necessary, 21 said yes, 1 said no, 5 were unsure, and 2 abstained. Some of the reasons given are listed in Table 1. Most of the therapists indicated a desire for active assistive type exercises. When asked what exercises they would use the active device for, the most common answer was to assist in functional movements (Table 1). The results shown in Fig 2 also provide some insight into why the therapists had a positive view of the need for a robotic device: they spend a large part of their time on manual manipulation of the upper extremity, especially in the acute stage of recovery. The therapists also believed that active assistance was an important technique for promoting motor recovery after stroke.

TABLE 1. SURVEY RESULTS FROM 29 THERAPIST FOR ACTIVE ORTHOSIS QUESTIONS.

Answers to Q: Are the robotic properties of an active orthosis needed? If so why?	
# of therapists responding	*Responses for those therapists that said yes.*
3	Assist weakened patients to perform movements.
3	Assist to complete initiated movements.
2	Assist with repetitive motions.
2	Improve Range of Motion and strength.
2	Stretching.
2	Documentation of patient's ability.
1	Provide balanced assistance / resistance.
Answers to Q: What kind of exercise would you use the active orthosis for?	
14	Functional tasks (lifting, eating).
4	Active/Passive Range of Motion.
3	Active Assist Range of Motion.
1	Strengthening, and stretching.

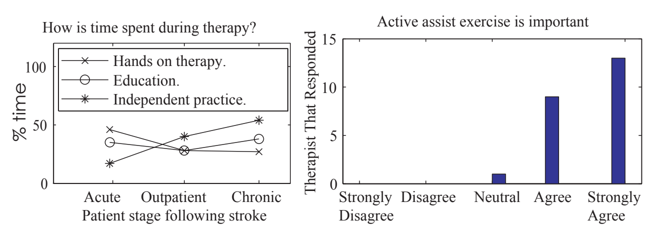

Figure 2: Results of a survey given to 29 practicing therapists who work with stroke survivors. Left: The therapists were asked to explain how much of therapy time is spent on rehabilitation education, hands on therapy with a therapist, and independent therapy, over three chronological stages of stroke. Right: The therapists were asked on a 5 point scale from strongly agree to strongly disagree, how important they thought active assist exercise is to recovery. No therapist responded with strongly disagree nor disagree.

Based on this input, we are developing a robotic version of WREX called Pneumatic-WREX (Pneu-WREX). Our goal is to develop a device that can safely apply a wide range of forces to the arm during naturalistic movement. We intend to use the device in a clinical setting for therapy and research.

II. Design Description of Pneu-WREX

Several robotic devices for movement training of the arm have been developed previously, including MIT-MANUS, MIME, the ARM Guide, and Gentle-S [8, 10-12]. None of these devices, however, has achieved the power and dexterity of a therapist's own hands. One reason is that it is very difficult to create a device with a large number of degrees of freedom but still have the ability to generate large forces with a good dynamic range (like a therapist's assistance). Our solution to this problem is to combine the passive counterbalance of T-WREX, pneumatic actuators (cylinders with pistons), and non-linear force control. The gravity counterbalance pre-biases the actuators to operate near their zero force point in the steady-state condition of support against gravity, so an actuator of a given size can operate with approximately twice the range possible without counterbalance. Pneumatic actuators have the advantage of producing large forces with a low on-board weight. In addition, pneumatic actuators can maintain high forces without energy expenditure since the pressure of a cylinder can be maintained simply by closing a valve. Non-linear force control techniques can give pneumatic actuators excellent active backdriveability and position controllability [13, 14].

A. Mechanical Design

Fig. 3 shows the design for the Pneu-WREX and the initial prototype. The orthosis is designed with 83° of shoulder flexion. Starting at 90° of shoulder flexion, the subject can move 47° of flexion to reach 137° of flexion, or 36° in extension to reach 54° of flexion. From the parasagittal plane the arm can be brought across the mid line to achieve 25° protraction, or 90° of retraction.

Pneu-WREX can accommodate upper arm lengths of 25.4-35.6cm (10-14in). The elbow can be removed and flipped for use with both the left and right arm. Pneu-WREX uses springs in place of rubber bands to bias it to the counterbalance level for the weight of an average arm. Pneu-WREX uses BIMBA low-friction pneumatic cylinders with a diameter of 38mm at four of the degrees of freedom, and 27mm at the forearm (the forearm cylinder is not depicted in Fig. 3).

Actuation of the elbow is accomplished through the use of a four-bar linkage. Use of the linkage allowed the actuating cylinder to be placed away from the body in an orientation that was parallel to the device, and out of the way. Different methods were conceived for actuating the elbow such as the use of pulleys or gears to implement the conversion of linear motion to rotary motion. However, those methods were too cumbersome or costly. One consequence of the four-bar linkage however, is that it couples the movements of the upper arm cylinder with the elbow cylinder.

B. Sensor and Control Hardware Selection

We desired a sensor that did not require zeroing, so that users of the system would not be required to execute an initialization procedure in order for the device to accurately measure movements or initiate assistance. Conductive plastic potentiometers (Midori America, CP-2FB) were chosen due to size, low weight, cost, life, and absolute position measurement with a linearity of 0.5%. The pneumatic cylinders chosen are also equipped with a Linear Resistive Transducer with virtually infinite resolution with a linearity of +/-1% of full stroke (BIMBA, PFC). The sensor redundancy provides a measure of safety in the event of sensor failure. Pressure sensors (Honeywell, ASCX100AN) measure the pressure in each side of the cylinder. The system will be controlled with pneumatic servovalves (FESTO) using the XPC real-time operating system.

III. Analysis of Pneu-WREX Kinematics and Force Production Capability

A. Forward Kinematics

In order to use Pneu-WREX as a position tracking system or to compute the required cylinder forces to actuate the device, it is necessary to define the forward kinematic relationship between the measured joint angles and the user's hand position. We used the product of exponentials formulation for the forward kinematics [15]. The position of the tip of the forearm link p_t relative to a fixed reference frame located at the shoulder is (initial position depicted in Fig 3):

$$p_t = e^{\hat{\xi}_1\theta_1} e^{\hat{\xi}_2\theta_2} e^{\hat{\xi}_3\theta_3} e^{\hat{\xi}_4\theta_4} e^{\hat{\xi}_5\theta_5} e^{\hat{\xi}_6\theta_6} g_{st0}, \tag{1}$$

with the following joint twists:

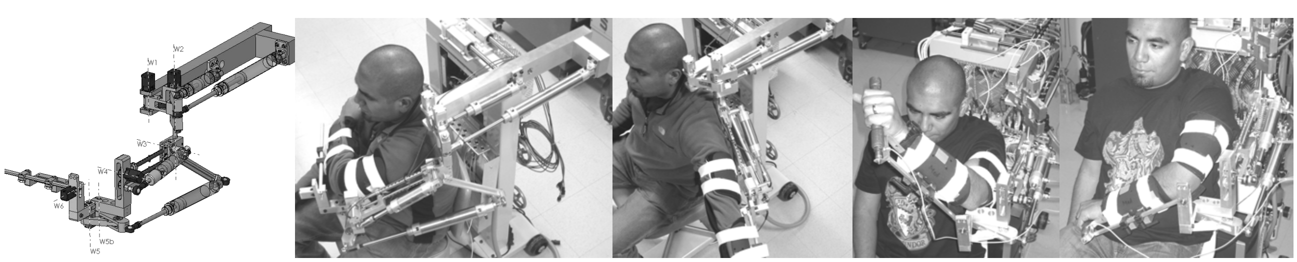

Figure 3. Pneu-WREX. Left: Solidworks Model of Pneu-WREX. Center & Right: Pneu-WREX Limits of Range of Motion.

$$\xi_1=\begin{bmatrix}0\\0\\0\\0\\0\\1\end{bmatrix},\ \xi_2=\begin{bmatrix}0\\3.91\\0\\0\\0\\1\end{bmatrix},\ \xi_3=\begin{bmatrix}0\\-v-3/2\\-7/5\\1\\0\\0\end{bmatrix},\ \xi_4=\begin{bmatrix}0\\-v-3/2\\-7/5-ua\\1\\0\\0\end{bmatrix},\ \xi_5=\begin{bmatrix}59/20+ua\\-9/100\\0\\0\\0\\1\end{bmatrix},\ \xi_6=\begin{bmatrix}3+v\\0\\9/100\\0\\1\\0\end{bmatrix},$$

and

$$g_{st0}=\begin{bmatrix}I_{3,3} & q_{t,0}\\0_{1,3} & 1\end{bmatrix},\ \mathrm{q}_{t,0}=\begin{bmatrix}607/50\\1141/200+ua\\-v-3\end{bmatrix}.$$

The initial location of the tip of the forearm is $q_{t,0}$, the angular displacements measured by the potentiometers are θ_i. The length of the upper arm is *ua*, the vertical displacement at the shoulder is *v*. (All kinematic equations are in inches.)

The product of exponential formulation is used to determine the position of each piston's two mounting points. The distance between the two mounting points is the cylinder length. The exponential formulas for each of the cylinder mounting points were determined in a manner similar to (1). However, the mounting points at the cylinder driving the four-bar mechanism required a solution for a four-bar mechanism sub-problem in order to determine the joint angles of the mechanism. The joints of the four-bar have been labeled in the standard method for identifying the joints and angle measurements in Fig 4[16].

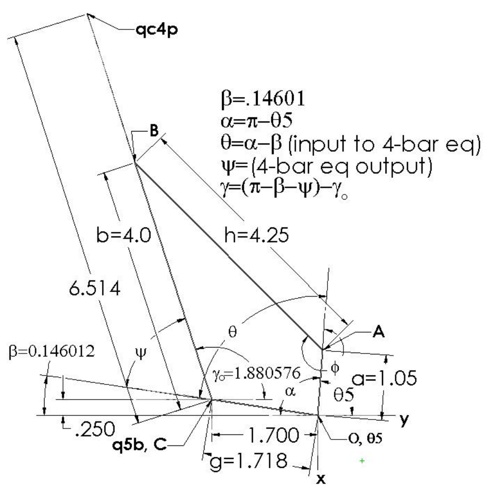

Figure 4. Four-Bar Mechanism, Joint Definition.

The solution for the four bar mechanism is:

$$\psi=\tan^{-1}\left(\frac{B(\theta)}{A(\theta)}\right)-\cos^{-1}\left(\frac{C(\theta)}{\sqrt{\left(A^2(\theta)+B^2(\theta)\right)}}\right). \qquad (2)$$

Where,

$A(\theta)=2ab\cos(\theta)-2gb.$

$B(\theta)=2ab\sin(\theta).$

$C(\theta)=g^2+b^2+a^2-h^2-2ag\cos(\theta).$

The exponential formulation for the mounting point of the piston to the four bar (qc4p) is:

$$q_{c4p}=e^{\hat{\xi}_1\theta_1}e^{\hat{\xi}_2\theta_2}e^{\hat{\xi}_3\theta_3}e^{\hat{\xi}_4\theta_4}e^{\hat{\xi}_{5b}\gamma}g_{stqc4p,0}, \qquad (3)$$

Where,

$$\gamma=\pi-\beta-\psi(rad). \qquad (4)$$

$$g_{stqc4p,0}=\begin{bmatrix}I_{3,3} & q_{c4p,0}\\0_{1,3} & 1\end{bmatrix},\ \mathrm{q}_{c4p,0}=\begin{bmatrix}-6.574\\-6.8\\-11.5368\end{bmatrix}.$$

B. Piston Velocity to Joint Angle Velocity Jacobian

The piston velocities were calculated by taking the derivative of the squared piston-length:

$$\frac{d}{dt}\left[x_{pi}^2=\left\|\left(p_{fi}^S-p_{bi}^S\right)\right\|^2\right]. \qquad (5)$$

Where,

x_{pi} =length of i[th] piston (scalar, in).

p_{fi}^S = Homogeneous point w/rt Spatial frame for piston mounting point *front* for i[th] piston, form (x, y, z, 1) (4x1).

p_{bi}^S = Homogeneous point w/rt Spatial frame for piston mounting point *back* for i[th] piston, form (x, y, z, 1) (4x1).

Equation (5) was solved for the velocity of the piston length:

$$\dot{x}_{pi}=\frac{1}{x_{pi}}\left(p_{fi}^S-p_{bi}^S\right)^T\left(\dot{p}_{fi}^S-\dot{p}_{bi}^S\right). \qquad (6)$$

Since the spatial velocity of a point $\dot{p}_i^S$ was defined as [15]:

$$\dot{p}_i^S=\left(J_{i(6x8)}^S\dot{\vartheta}_{(8x1)}\right)^{\wedge}_{(4x4)}p_{i(4x1)}^S, \qquad (7)$$

Where,

$J_{i,n}^S$ =Spatial Jacobian for piston mounting point for i[th] piston, for n[th] axis of rotation (6x1).

$\dot{\vartheta}$ =angular velocities $\left[\dot{\theta}_1,\dot{\theta}_2,\dot{\theta}_3,\dot{\theta}_{3b},\dot{\theta}_4,\dot{\theta}_5,\dot{\theta}_{5b},\dot{\theta}_6\right]^T$.

Then (6) was rewritten as:

$$\dot{x}_{pi}=\frac{1}{x_{pi}}\left(p_{fi(4x1)}^S-p_{bi(4x1)}^S\right)^T_{(1x4)}\left[J_{axis,i}\right]_{(4x8)}\dot{\vartheta}_{(8x1)}. \qquad (8)$$

Where,

$$J_{axis,i}=\left[J_{ax1,i},J_{ax2,i},J_{ax3,i},J_{ax3b,i},J_{ax4,i},J_{ax5,i},J_{ax5b,i},J_{ax6,i}\right]_{(4x8)}.$$

$$J_{ax(n),i}=\left[\left(\left(J_{fi(6x1),n}^S\right)^{\wedge}_{(4x4)}p_{fi(4x1)}^S\right)_{(4X1)}-\left(\left(J_{bi(6xi),n}^S\right)^{\wedge}_{(4x4)}p_{bi(4x1)}^S\right)\right]_{(4x1)}.$$

$J_{fi,n}^S$ =Spatial Jacobian for piston mounting point *front* for i[th] piston, for n[th] axis of rotation (6x1).

$J_{bi,n}^S$ = Spatial Jacobian for piston mounting point *back* for i[th] piston, for n[th] axis of rotation (6x1).

C. Force Calculations

A relationship between the pistons' forces f_p required to balance the forces exerted by the arm F_{arm} was derived from the power equation. The power equation relates the cylinder forces and piston velocity $\dot{x}_p$ to the forces of the arm and spatial arm velocity V_{arm}^S:

$$F_{arm}^T V_{arm}^S=f_p^T\dot{x}_p. \qquad (9)$$

Since $V^S=J^S\dot{\vartheta}$, (9) is rewritten as:

$$F_{arm}^T J_{arm}^S\dot{\vartheta}=f_p^T\dot{x}_p. \qquad (10)$$

$$\text{Let } \dot{x}_p = J_P \dot{\vartheta}. \quad (11)$$

Where,

$$J_{P_i,(1X5)} = \frac{1}{x_{pi}} \left(p^S_{fi(4x1)} - p^S_{bi(4x1)} \right)^T_{(1x4)} J_{axis,i(4x8)}.$$

$$J_{P(5X8)} = \begin{bmatrix} J_{P_1} & J_{P_2} & J_{P_3} & J_{P_4} & J_{P_5} \end{bmatrix}^T.$$

Then applying (11) to (10) yields:

$$F^T_{arm} J^S_{arm} \dot{\vartheta} = f^T_p J_P \dot{\vartheta}. \quad (12)$$

Since $\theta_3 = \theta_{3b}, \theta_3 = -\theta_4$, $\dot{\vartheta}$ can be redefined as a function of reduced angular velocities $\dot{\vartheta}_{reduced}$:

$$\dot{\vartheta} = P \dot{\vartheta}_{reduced}. \quad (13)$$

Where,

$$P_{piston} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\dot{\gamma}(\theta_5) & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, P_{arm} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \dot{\vartheta}_{reduced} = \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{\theta}_5 \\ \dot{\theta}_6 \end{bmatrix},$$

$$\dot{\gamma} = \frac{a\sin(\phi)}{b\sin(\theta + \phi - \psi)} \dot{\theta} \text{ [16] (From Fig 4: } \dot{\theta} = -\dot{\theta}_5\text{)}, \quad (14)$$

Equation (13) was applied to (12) to yield:

$$F^T_{arm} J^S_{arm} P_{arm} \dot{\vartheta}_{reduced} = f^T_p J_P P_{piston} \dot{\vartheta}_{reduced}. \quad (15)$$

Equation (15) reduced to:

$$P^T_{arm} J^{S,T}_{arm} F_{arm} = P^T_{piston} J^T_P f_P. \quad (16)$$

Equation (16) was solved for the piston force f_p as a function of a desired load at the forearm:

$$f_{p(5X1)} = [P^T_{piston(5X8)} J^T_{P(8X5)}]^{-1}_{(5X5)} P^T_{arm(5X8)} J^{S,T}_{arm(8X6)} F_{arm(6X1)}. \quad (17)$$

or (16) may be solved for the force exerted by the robot as a function of the piston forces:

$$F_{arm(6X1)} = [P^T_{arm(5X8)} J^{S,T}_{arm(8X6)}]^{-1}_{(6X5)} P^T_{piston(5X8)} J^T_{P(8X5)} f_{p(5X1)}. \quad (18)$$

Equation (18) was used to determine that Pneu-WREX will be able to generate ±89N (20*lbf*) of vertical force at the location of the arm attachment point, given an operating pressure of 531kPa (77psi), with the arm in the home configuration shown in Fig 3.

IV. Discussion and Conclusion

This paper has described the rationale for and the design of a pneumatic robot for retraining arm movement after stroke. Pneu-WREX will use pneumatic actuators, non-linear force control, and passive counterbalancing to allow application of a wide range of forces during naturalistic movement. Based on our experience with a pneumatic gait-training robot that we have developed [14], we expect to achieve a position control bandwidth of at least 4 Hz. We are hopeful that Pneu-WREX will provide a useful new tool for optimizing robotic therapy.

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