CONTROL OF A POWERED, GRAVITY-BALANCED ORTHOSIS FOR CHILDREN WITH LIMITED UPPER LIMB STRENGTH

by

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# TABLE OF CONTENTS

LIST OF TABLES ....................................................................................... vi
LIST OF FIGURES .................................................................................... vii
ABSTRACT ................................................................................................. x

Chapter

1 INTRODUCTION .................................................................................. 1

2 BACKGROUND .................................................................................... 3

3 SERIES ELASTIC ACTUATORS ............................................................ 7

3.1 Dynamic Model ............................................................................. 7

3.1.1 Torsional .................................................................................. 9
3.1.2 In-line ...................................................................................... 12

3.2 Controller ...................................................................................... 14
3.3 Simulation ...................................................................................... 15

3.3.1 Dynamic Simulation ................................................................. 15

3.4 Experiment .................................................................................... 20
3.5 Discussion ..................................................................................... 23
3.6 Conclusion .................................................................................... 24

4 THE CONTROL OF SERIES ELASTIC ACTUATORS ...................... 25

4.1 Dynamic Equations ........................................................................ 25
4.2 Control .......................................................................................... 26
4.3 Simulation and Experimentation ..................................................... 27
4.4 Discussion ..................................................................................... 30

5 QUANTIFYING ANTI-GRAVITY TORQUES FOR THE DESIGN OF A
POWERED EXOSKELETON ................................................................. 32

5.1 Introduction ................................................................................... 32
5.2 Joint Torque Measurements .......................................................... 35

5.2.1 Human Model ........................................................................ 35
5.3 Experimental Protocol ................................................................... 36
5.4 Results .......................................................................................... 39
LIST OF TABLES

Table 1: Physical Parameters........................................................................................................16
Table 2: Subject Groups ..................................................................................................................36
Table 3: Coefficients for the best-fit, third-degree polynomial of normalized joint torques ..........................................................43
Table 4: Joint ranges, maximum applied joint torques, and average torques for children with disabilities........................................................................43
Table 5: Joint Torque Data ...........................................................................................................54
Table 6: Polynomial Coefficients of Curve Fit for Joint Torque Data........................................55
Table 7: Active Movement Scale ................................................................................................62
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Picture of user in passive WREX. The anthropomorphic design and gravity balancing springs can be seen.</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Physical Parameters of the WREX.</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>Schematic of series elastic actuation in parallel to gravity balancing springs.</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>Schematic of series elastic actuation in-line to gravity balancing springs.</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>Shoulder Elevation from Simulation.</td>
<td>17</td>
</tr>
<tr>
<td>6</td>
<td>Elbow Elevation from Simulation.</td>
<td>18</td>
</tr>
<tr>
<td>7</td>
<td>Shoulder Torque from Simulation.</td>
<td>18</td>
</tr>
<tr>
<td>8</td>
<td>Elbow Torque from Simulation.</td>
<td>19</td>
</tr>
<tr>
<td>9</td>
<td>Experimental Setup.</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>Shoulder Elevation from Experiment</td>
<td>21</td>
</tr>
<tr>
<td>11</td>
<td>Elbow Elevation from Experiment.</td>
<td>21</td>
</tr>
<tr>
<td>12</td>
<td>Shoulder Torque from Experiment.</td>
<td>22</td>
</tr>
<tr>
<td>13</td>
<td>Elbow Torque from Experiment.</td>
<td>22</td>
</tr>
<tr>
<td>14</td>
<td>Schematic of Series Elastic Actuator</td>
<td>25</td>
</tr>
<tr>
<td>15</td>
<td>Block Diagram of Torque Control</td>
<td>26</td>
</tr>
<tr>
<td>16</td>
<td>Picture of Experimental Setup</td>
<td>27</td>
</tr>
<tr>
<td>17</td>
<td>Step Response of Control on Series Elastic Actuator</td>
<td>28</td>
</tr>
<tr>
<td>18</td>
<td>Bode Diagram of Torque Control on Series Elastic Actuator</td>
<td>29</td>
</tr>
<tr>
<td>19</td>
<td>Children wearing 2 versions of the passive WREX. Image on left shows the WREX attached to a wheelchair, and image on right shows attached to a body jacket for children that are ambulatory.</td>
<td>33</td>
</tr>
</tbody>
</table>
Figure 20: Model of upper limb as two rigid links with given variables. The symbols $q_1$ and $q_2$ are the shoulder and elbow angles, $\tau_1$ and $\tau_2$ are joint torques, $m_1g$ and $m_2g$ are the gravity forces, and $F_x$, $F_y$, and $\tau_2$ are the measured forces and torque between the human and the measuring device. The force sensor is located at the origin of the force vectors. ... 35

Figure 21: Measuring device with lockable joints at the shoulder and elbow with a force sensor attached to the arm trough. The subjects forearm is strapped to the arm trough and locked at various positions. .................. 37

Figure 22: Average joint torques normalized to subjects’ weight and arm length. The arm figures in the upper left graph represent the arm configuration of each section of the graph. The left column is for the shoulder and the right column is for the elbow. The top two graphs are for adults, middle two for children, and bottom two for both groups combined. The dots are data points. The surface is the best fit polynomial................................................................. 40

Figure 23: Cross section of average joint torques normalized to subjects’ weight and arm length. Left column is with the elbow locked at zero degrees. The right column is with the shoulder locked at ninety degrees. The arm figures provide visual representation of the arm orientation. The grey line is the torque expected from the two link lump mass model..... 41

Figure 24: Normalized joint torques due to gravity of children with disabilities. For each subject the top graph is for the shoulder and the bottom graph is for the elbow................................................................. 44

Figure 25: Cross section of passive joint torques normalized to subjects weight and arm length. The typical children are averaged and shown as a solid line. Each disabled child is shown separately and subject number corresponds to Table 3. ........................................................................................................ 45

Figure 26: Maximum applied torque data of children with disabilities. The upper surface is for contracting the arm upwards. The lower surface is for extending the arm downwards................................................................. 46

Figure 27: Picture of person wearing powered WREX. Motors are at the shoulder and elbow joint. The force sensor is attached to the bottom of the arm trough under the forearm................................................................. 51

Figure 28: Data and curve fit of passive joint torques at the shoulder and elbow. ...... 56

Figure 29: Elbow Flexion Against Gravity with Friction Compensation .................. 58
Figure 30: Elbow Flexion Against Gravity with Torque

Figure 31: Elbow Flexion Against Gravity with Torque

Figure 32: Elbow Flexion Against Gravity with joint angle and motor torques

Figure 33: Elbow Flexion Against Gravity with joint angle and human torque
ABSTRACT

There are several pediatric musculoskeletal diseases, such as muscular dystrophy, spinal muscular atrophy, and arthrogryposis, characterized by upper limb weakness with minimal or abnormal motor control and sensation. Often a person with one of these conditions is not able to be independent and requires assistance to perform activities of daily living. Specifically, among other gross motor challenges, these patients often are too weak to overcome the weight of their own arm for daily tasks including self-feeding. There have been several engineering devices designed to increase patients’ independence through decreasing the power required to perform upper extremity (UE) tasks. One example is the WREX (Wilmington Robotic Exoskeleton), a currently commercialized passive, pediatric, upper-limb orthosis designed to assist children with upper limb weakness. The WREX has an anthropomorphic configuration and uses parallel mechanisms with zero rest-length springs for gravity balancing.

Due to limitations including 1) lack of countering force to allow the child to pick up objects of significant weight and 2) difficulty for the children to raise their arm above their head due to misalignment of joints between user and device and/or possible increasing device joint stiffness with shoulder elevation, it was proposed to add motors and a controller to the WREX to increase UE function. Series Elastic Actuation (SEA) was proposed to maintain a compliant interaction between the device...
and user. However, testing indicated an instability problem, requiring rigid fixation of the motors to the device instead of SEA.

After the motors were attached, the problem of human intention needed to be solved. To do this, a 6-axis force sensor was installed at the forearm between the WREX and the user to detect user intention. A force sensor was used to make the control intuitive for the user. Results indicated that an individual static model for each user was needed to extract the user intention from the sensed force. Three different control laws were implemented – (i) friction compensation, as a baseline, (ii) sensed force proportional to control torque; (iii) sensed force proportional to control velocity.

Preliminary testing showed that the control laws were able to detect the direction of intended motion, but further, larger studies are merited to determine any superiority of the control laws. Future work should also include testing more sophisticated control laws, and miniaturizing of the device in order to make it feasible for home use.
Chapter 1

INTRODUCTION

There are several pediatric musculoskeletal diseases, such as muscular dystrophy, spinal muscular atrophy, and arthrogryposis, characterized by upper limb weakness with minimal or abnormal motor control and sensation. Often a person with one of these conditions requires assistance to perform activities of daily living. Specifically, among other gross motor challenges, these patients often are too weak to overcome the weight of their own arm for daily tasks including self-feeding. The WREX (Wilmington Robotic Exoskeleton) is a passive pediatric, upper-limb orthosis designed to help children counteract upper limb weakness secondary to such musculoskeletal diseases [1] shown in Fig. (1). The WREX has an anthropomorphic configuration and uses parallel mechanisms with zero rest-length springs for gravity balancing. The WREX is theoretically statically balanced in all configurations. The WREX is primarily used for daily assistance, unlike most other devices, which are used for rehabilitation [2-4]. However, the WREX can be modified to be useful also for rehabilitation purposes [5, 6].
Two limitations of the WREX have been noticed, however. (i) A user is unable to pick up an object of significant weight, because the device effectively balances only the weight of the user's arm; (ii) Users have difficulty raising their arm above their head, likely due to misalignment between the joints of the user and the device and/or increased joint stiffness in the shoulder at higher degrees of elevation. It has therefore been proposed to investigate adding motors and a controller to provide patients with greater and more functional UE function.
Chapter 2

BACKGROUND

Many powered devices have been created to assist both fully able and disabled humans in a variety of tasks. Powered devices are typically used either to augment normal human strength, and are called amplifiers, or to supplement the lack of strength in people with physical disabilities. The latter typically are constructed as exoskeletons, and are usually designed for the upper or lower extremity exclusively. These powered devices used for supplementing strength in the physically disabled can also be subdivided as used for rehabilitation purposes or for assistance with daily activities of living.

Research on powered exoskeletons started in the 1960s when General Electric created a ‘man amplifier’ called the Handiman [7]. The Handiman was a full-body exoskeleton. It was hydraulically actuated and could pick up objects as heavy as 1000 lbs. under the control of a human user. The Handiman, however, was not successful due to unresolved stability issues. The work of designing human exoskeletons for augmenting human strength has continued since then in the military research. The most advanced exoskeleton of this type currently in development today is likely the Human Universal Load Carrier (HULC), developed at UC Berkeley [8]. The HULC is a battery powered lower limb exoskeleton developed for the US Army that can carry a 200 lb. load with minimal effort for the user. Augmenting human strength continues to be a large focus in robotics research, used primarily for military and industry purposes.

In addition to the research of augmenting human strength, powered devices have also been used to supplement human strength. One recent full-body exoskeleton
has been developed in Japan to assist physically disabled subjects, called the Hybrid Assistive Limb (HAL) [9]. The HAL uses EMG signals from the patient to detect motion and amplifies the signal. It is currently undergoing clinical trials in Japan, and is one example of a full-body exoskeleton used to supplement strength. Typically, however, most research on powered devices meant to supplement strength for people with physical disabilities is most effective when focusing exclusively on either the upper or lower extremity.

Several upper-limb orthoses exist today. A majority of these are used for rehabilitation only, not for daily assistance, due in part to their high cost and complexity. For instance, Hogan et al. in 1998 designed a direct drive, five-bar-linkage SCARA (Selective Compliance Assembly Robot Arm) called the MIT-MANUS [2] to aid in stroke rehabilitation of the upper limb. The MIT-MANUS functioned in a horizontal plane and worked with visual feedback to assist users to perform predefined arm movements in therapy. Interestingly, the outcomes of this study indicated that the device yielded therapeutic benefits similar to those of traditional therapy. A more recent research project in 2006 using a PUMA 560 robot and mobile arm supports, by Lum et al., developed the Mirror Image Movement Enabler (MIME) robotic device, to enable bilateral upper extremity rehabilitation for stroke patients[4]. The MIME had 6 degrees of freedom. It involved bilateral upper extremity movement with the intent to promote neural changes within the brain to compensate for the affected hemisphere in controlling the paretic limb, and suggested feasibility of this type of design and yielded therapeutic benefits. Reinkensmeyer developed the ARM Guide (Assisted Rehabilitation and Measurement Guide) to diagnose movement impairments and provide therapy in a single reaching direction for
stroke patients [3]. The reaching direction could be angled in a large 3D work space. The ARM Guide used a control law that only assisted after the user initiated movement. The level of assistance was progressively modified to provide enough help to complete the task, but also provide a challenge to the user. This user-initiated, continuously adaptive assistance showed improved results over the MIT-MANUS and MIME. Finally, in contrast to these rehabilitative machines, one assistive device that is intended for daily assistance versus rehabilitation is the Armon, developed by Herder et al [10] using a passive (non-powered) balancing device of cams and springs. This device was shown to effectively improve its users’ ability to complete activities of daily living.

Likewise, the WREX was designed not to act as a rehabilitation device, like most of the previous designs, but to act as a tool for daily assistance, similar to the Armon. The unique properties of the WREX are the anthropomorphic design and gravity balancing springs, categorizing it as a passive (non-powered) device for the upper extremity, which greatly increase the range-of-motion of most of its physically disabled users. However, the current version of the WREX and the purpose of this present research investigation is to provide even greater assistance to the user, through the addition of motors and a controller. Thus, we propose that the WREX can provide increased assistance with activities of daily living as a motor-assistive device vs a non-motorized device.

The target population of the WREX device is pediatrics with upper limb weakness, but with some degree of residual motor control, flexibility, and sensation. The most common conditions that satisfy these inclusion criteria include SMA, arthrogryposis, and MD. Children with complete upper limb paralysis are not included
because of total lack of control. Children with cerebral palsy also typically cannot be
included because joint stiffness and spasticity are incompatible with the design of the
device. Children with SMA, arthrogryposis, and MD have difficulty in completing
Activities of Daily Living. These children often need assistance to dress and feed
themselves. The passive WREX was designed to assist this population, and the
proposed powered WREX is designed to provide even greater benefit.
Chapter 3

SERIES ELASTIC ACTUATORS

We propose using electric motors along with springs in a way that provides “softness” to the user. This can be realized by using series elastic actuators, which are preferable to the traditional stiff systems operating in natural environments [11]. The addition of motors should have a limited effect on the user, because the motor weight can be gravity balanced. Based on this proposal, this research addressed the following issues:

1) Compares the torque requirements of two different series elastic actuator placements in gravity balanced mechanisms, namely the WREX.

2) Novelty in the controller development using a fourth order model of the governing equations.

3.1 Dynamic Model

The two different motor placements are shown in a two-dimensional schematic in Figs. (3) and (4). The current WREX device has a total of 4 degrees of freedom (DOFs) including two joints that allow rotation around a vertical axis at the shoulder and elbow and two that allow rotation around horizontal axes at the shoulder and elbow. The model used in this paper neglects the rotation about the vertical axes and only considers motion in the gravitational plane. This simplification is valid as the motors only assist against gravity and not in the transverse plane. The torsional case is shown in Fig. (3), where the motors are connected to the joints using additional torsion springs. The in-line case is shown in Fig. (4), where the motors are connected in series with the gravity balancing spring. The upper link, which is shown as a thin line in Fig. (3) and Fig. (4), is assumed massless. Spring constant, $k$, values were
appropriately chosen according to the gravity balancing algorithm by Rahman [12] to balance the weight of the device. One of the goals of the WREX project is to allow a wearer to manipulate a mass. Therefore a point mass was modeled at the end of the device. Because the goal of this paper was to investigate placement of the motors, the motors were considered ideal with no resistance, friction, or damping.

![Physical Parameters of the WREX](image)

Figure 2: Physical Parameters of the WREX

The dynamic equations were obtained using the Lagrange method described by Spong and Vidyasagar [13] for modeling a motor coupled to a spring mass system. Two sets of dynamic equations are derived: one set for the arm linkage and one set for the motors. The equations for the arm are substituted into the equations for the motor, which leaves the motor torque as a function of only the arm angles and their derivatives. This is shown step by step in the following sections. Physical parameters referred to in the subsequent sections are shown in Fig. (2)
3.1.1 Torsional

Figure 3: Schematic of series elastic actuation in parallel to gravity balancing springs.

The dynamic equations for the linkages are:

\[ D(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} + g(\theta) + s(\theta) - K_m \theta_m = 0, \]  

where \( D(\theta) \) is the inertia matrix,

\[ D(\theta) = \begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix}, \]  

and

\[ d_{11} = l_2 + m_5L_2^2 + m_4L_2^2 + m_2Lc_2^2 + m_3L_2^2, \]

\[ d_{12} = d_{21} = m_4L_2 \sin(\theta_1) Lc_4 \sin(\theta_2) + m_4L_2 \cos(\theta_1) Lc_4 \cos(\theta_2) + m_5L_2 \sin(\theta_1) L_4 \sin(\theta_2) + m_5L_2 \cos(\theta_1) L_4 \cos(\theta_2), \]
\[ d_{22} = I_5 + m_5 L_4^2 + m_4 L c_4^2 + l_4, \quad (5) \]

\( C(\theta, \dot{\theta}) \) is the centrifugal and Coriolis matrix,

\[
C(\theta, \dot{\theta}) = \begin{bmatrix}
0 & c_{12} \\
c_{21} & 0
\end{bmatrix},
\quad (6)
\]

where,

\[
c_{12} = (-m_4 L_2 \cos(\theta_1) L_4 \sin(\theta_2) - m_5 L_2 \cos(\theta_1) L_4 \sin(\theta_2)) \\
+ m_5 L_2 \sin(\theta_1) L_4 \cos(\theta_2) + m_4 L_2 \sin(\theta_1) L_4 \cos(\theta_2) \dot{\theta}_2, \\
\quad (7)
\]

\[
c_{21} = (m_4 L_2 \cos(\theta_1) L_4 \sin(\theta_2) - m_5 L_2 \sin(\theta_1) L_4 \cos(\theta_2)) \\
- m_4 L_2 \sin(\theta_1) L_4 \cos(\theta_2) + m_5 L_2 \cos(\theta_1) L_4 \sin(\theta_2) \dot{\theta}_2, \\
\quad (8)
\]

\( g(\theta) \) is the gravitational vector,

\[
g(\theta) = \begin{bmatrix}
g(m_2 L c_2 \sin(\theta_1) + m_3 L_2 \sin(\theta_1) + m_4 L_2 \sin(\theta_1) + m_5 L_2 \sin(\theta_1)) \\
\quad \\
g(m_5 L_4 \sin(\theta_2) + m_4 L_4 \sin(\theta_2))
\end{bmatrix}, \quad (9)
\]

\( s(\theta) \) is the spring potential term from the gravity balancing spring and the motor spring,

\[
s(\theta) = \begin{bmatrix}
-k_1 a_1 b_1 \sin(\theta_1) + k_3 \theta_1 \\
-k_2 a_2 b_2 \sin(\theta_2) + k_4 \theta_2
\end{bmatrix}, \quad (10)
\]

\( K_m \) is a matrix of motor spring stiffness

\[
K_m = \begin{bmatrix}
k_3 & 0 \\
0 & k_4
\end{bmatrix}, \quad (11)
\]
and \( \theta \) is the vector of arm angles. The equation is set to zero, because there are no external torques being applied. The vectors \( \theta \) and \( \theta_m \) are given by:

\[
\theta = \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix}, \quad \theta_m = \begin{bmatrix} \theta_3 \\ \theta_4 \end{bmatrix},
\]

(12)

where \( \theta_3 \) is the shoulder motor angle and \( \theta_4 \) is the elbow motor angle. The dynamic equations for the ideal motors are given by:

\[
D_m \ddot{\theta}_m + s_m(\theta, \theta_m) = u_m,
\]

(13)

where \( D_m \) is the motor inertia matrix,

\[
D_m = \begin{bmatrix} I_m & 0 \\ 0 & I_m \end{bmatrix},
\]

(14)

The \( s_m(\theta, \theta_m) \) term is the spring potential term from the spring between the motor and the arm,

\[
s_m(\theta, \theta_m) = \begin{bmatrix} k_3(\theta_3 - \theta_1) \\ k_4(\theta_4 - \theta_2) \end{bmatrix},
\]

(15)

and \( u_m \) is the motor input given by:

\[
u_m = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}.
\]

(16)

The equation for the device (1) can be solved for \( \theta_m \).

\[
\theta_m = K_m^{-1}[D(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} + g(\theta) + s(\theta)]
\]

(17)

One note is that if the friction were included in the model, \( \theta_m \) could not be solved for in this manner, and the subsequent controller could not be achieved. This
equation for $\theta_m$ and its double derivative can be substituted into the dynamic motor equation (13). This substitution leaves $u_m$ as an equation of the form,

$$u_m = A(\theta)\ddot{\theta} + b(\ddot{\theta}, \dot{\theta}, \theta)$$  \hspace{1cm} (18)

Maple was used to solve the equation.

3.1.2 In-line

![Series Elastic Actuation Diagram](image)

Figure 4: Schematic of series elastic actuation in-line to gravity balancing springs.

The dynamic equations for the linkages are:

$$D(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} + g(\theta) + s_2(\theta) - S_r(\theta)\theta_m = 0,$$  \hspace{1cm} (19)

where all the terms are the same as in (1) except $s_2(\theta)$ is the spring potential vector,

$$s_2(\theta) = \begin{bmatrix} -k_1a_1b_1\sin(\theta_1) \\ -k_2a_2b_2\sin(\theta_2) \end{bmatrix}.$$  \hspace{1cm} (20)
and $S_r(\theta)$ is the spring potential matrix from the spring winding around the spool,

$$S_r(\theta) = \begin{bmatrix} k_1 a_1 b_1 \sin(\theta_1) r_1 & 0 \\ \sqrt{a_1^2 + b_1^2 + 2a_1 b_1 \cos(\theta_1)} & k_2 a_2 b_2 \sin(\theta_2) r_2 \\ 0 & \sqrt{a_2^2 + b_2^2 + 2a_2 b_2 \cos(\theta_2)} \end{bmatrix}. \quad (21)$$

The $r$ values in (21) represent the radius of the spool, around which the spring is wound. Three values of $r$ were chosen, 0.02, 0.03, and 0.04, which provided a reasonable range considering physical space constraint.

The dynamic equations for the ideal motors are given by:

$$D_m(\theta_m) \ddot{\theta}_m + s_p(\theta, \theta_m) = u_m, \quad (22)$$

where $D_m(\theta_m)$ is the inertia matrix, as in (13).

$$s_p(\theta, \theta_m) = \begin{bmatrix} k_1 r_1 \sqrt{a_1^2 + b_1^2 + 2a_1 b_1 \cos(\theta_1)} + k_1 r_1^2 \theta_3 \\ k_2 r_2 \sqrt{a_2^2 + b_2^2 + 2a_2 b_2 \cos(\theta_2)} + k_2 r_2^2 \theta_4 \end{bmatrix}. \quad (23)$$

The equation for the device (19) can be solved for $\theta_m$.

$$\theta_m = S_r(\theta)^{-1} [D(\theta) \ddot{\theta} + C(\theta, \dot{\theta}) \dot{\theta} + g(\theta) + s_2(\theta)]. \quad (24)$$

This equation for $\theta_m$ can be substituted into the dynamic motor equation (22). This substitution leaves $u_m$ as an equation of a similar form of (18), but with different coefficients,
\[ u_m = M(\theta) \ddot{\theta} + n(\ddot{\theta}, \dot{\theta}, \theta). \]  

(25)

One note is that due to \( S_r(\theta)^{-1} \), there are singularities at 0 and \( \pi \) in the in-line case, which correspond to the vertical down and vertical up positions, respectively; however this will not be a problem because the device does not operate past those positions.

3.2 Controller

According to Spong [14], a PD controller on a joint with flexibility provides poor results. Therefore, a computed torque method was applied to both setups. Also, since this research focused on motor placement, issues with human interaction will be addressed in future studies. The steps for the torsional controller will be shown. The in-line case follows the same procedure and will not be shown. The control law was chosen to be

\[ u_m = A(\theta)(\dddot{\theta}_d + k_j \ddot{e} + k_a \dot{e} + k_v e) + b(\ddot{\theta}, \dot{\theta}, \theta) \]  

(26)

where \( e \) is the error given by

\[  \ddot{e} = \ddot{\theta}_d - \ddot{\theta}, \dot{e} = \dot{\theta}_d - \dot{\theta}, e = \theta_d - \theta \]  

(27)

where \( \theta_d \) and its derivatives are the desired joint trajectories and its derivatives. When the control law (26) is set equal to (18), assuming the model is perfectly known, the error equation is given by:

\[ \dddot{e} + k_j \ddot{e} + k_a \dot{e} + k_v e = 0, \]  

(28)
Because the error equation (28) is the same for both cases the same gains were applied to both cases in order to fairly compare the response of the two cases. Gains were determined experimentally. The gains for the shoulder motor were: \( k_j = 65.2, k_1 = 1850, k_v = 26100, \text{and } k_p = 160000 \) and the gains for the elbow motor: \( k_1 = 62.0, k_a = 1670, k_v = 22400, \text{and } k_p = 130000 \).

### 3.3 Simulation

#### 3.3.1 Dynamic Simulation

For the dynamic simulation, the desired trajectory was obtained from a motion capture study of a patient performing an eating task while wearing a passive WREX device at the A.I. duPont Children’s Hospital in Wilmington, DE. A 4\(^{th}\) order polynomial was curve fit to the shoulder and elbow joint data, because up to the fourth derivative is required in the controller.

The equation of the shoulder elevation in radians as a function of time was approximated by:

\[
\theta_1 = 4.27t^4 - 10.87t^3 + 7.24t^2 - 0.46t + 0.50.
\] \( (29) \)

The equation of the elbow elevation in radians was approximated by:

\[
\theta_2 = -1.24t^4 + 2.15t^3 - 1.88t^2 + 1.54t + 2.02.
\] \( (30) \)

The polynomial and its derivatives were used as desired joint trajectories in both cases. The robot was given an initial 5\% error from the desired angles to test the tracking response.

The physical parameters are listed in Table 1.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Link 1</th>
<th>Link 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>$L_1$</td>
<td>$L_2$</td>
</tr>
<tr>
<td>COM (m)</td>
<td>$L_{c1}$</td>
<td>$L_{c2}$</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>$m_1$</td>
<td>$m_2$</td>
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<tr>
<td>Inertia (kg·m$^2$)</td>
<td>$I_1$</td>
<td>$I_2$</td>
</tr>
<tr>
<td>Length (m)</td>
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<tr>
<td>COM (m)</td>
<td>$L_{c3}$</td>
<td>$L_{c4}$</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>$m_3$</td>
<td>$m_4$</td>
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<tr>
<td>Inertia (kg·m$^2$)</td>
<td>$I_3$</td>
<td>$I_4$</td>
</tr>
<tr>
<td>Stiffness (N/m)</td>
<td>$k_1$</td>
<td>$k_2$</td>
</tr>
<tr>
<td>Height (m)</td>
<td>$a_1$</td>
<td>$a_2$</td>
</tr>
<tr>
<td>Length (m)</td>
<td>$b_1$</td>
<td>$b_2$</td>
</tr>
<tr>
<td>Stiffness (Nm/rad)</td>
<td>$k_3$</td>
<td>$k_4$</td>
</tr>
<tr>
<td>Inertia (kg·m$^2$)</td>
<td>$I_{m1}$</td>
<td>$I_{m2}$</td>
</tr>
<tr>
<td>Mass</td>
<td>$m_5$</td>
<td>0.1</td>
</tr>
</tbody>
</table>

$^1$ Link 1 assumed to be massless
The centers of mass were determined experimentally. The moments of inertia of the links were calculated as uniform round beams. Motor specifications came from the data sheet.

The joint angles and torque requirements for the dynamic simulation are shown in Figs. (5) – (8).

![Shoulder Elevation vs Time](image)

Figure 5: Shoulder Elevation from Simulation.
Figure 6: Elbow Elevation from Simulation.

Figure 7: Shoulder Torque from Simulation.
Both the in-line case and the torsional case were able to track the desired trajectory. The response of the torsional case and the response of the in-line case were nearly identical, shown in the overlapping trajectories in Fig. (5) and Fig. (6).

The torsional case has an absolute maximum torque value of approximately 1 Nm while the in-line case has an absolute maximum torque value of approximately 6 Nm, with an r value of 0.02m. In all simulations except one, the in-line case required a higher torque value that the torsional throughout the entire motion. The one exception was that the torque requirement at the elbow for the in-line case with an r value of 0.02 was similar to that for the torsional case, seen in Fig. (6). In all but one simulation, the in-line case required a higher torque value than the torsional case.
3.4 Experiment

An experimental setup was built to validate the simulated results of the torsional case. The setup is shown in Fig. (9).

![Experimental Setup](image)

**Figure 9: Experimental Setup**

Two Faulhaber brushed DC motors type 2342 S 012 CR with 23/1 gearheads of gear ratios 1/43 and 1/66 were attached at the shoulder and elbow, respectively. The motors were powered using two Advanced Motion Control 12A8 amplifiers. Four US Digital E4P Optical encoders recorded the joint angles. Two Analog Devices ADXL320 accelerometers measured acceleration. The device was connected to a target pc through a NI PCI-6040E and a NI-6601 DAQ board and controlled in realtime by Matlab xPC running at 100 Hz.

The experimental joint angles and torque requirements for the dynamic simulation are shown in Figs. (10) – (13).
Figure 10: Shoulder Elevation from Experiment

Figure 11: Elbow Elevation from Experiment.
Figure 12: Shoulder Torque from Experiment.

Figure 13: Elbow Torque from Experiment.
The device was able to track the given trajectory as shown in Figs. (10) – (13). The reference tracking was not as close as in the simulation because of model uncertainties and friction, which was not accounted for in the control. The required torques are higher than those in the simulation, also because of friction. There were minor oscillations in the elbow joint in Figs. (13) that are not present in simulation, because of a significant jump in the desired angular velocity at the beginning of the experiment.

3.5 Discussion

The simulations were run in order to determine which motor placement would be preferable. Although not the only measure, required torque is a significant measure, because a larger torque requires a larger and more expensive motor. In the dynamic simulations, the torsional case had a significantly lower torque requirement by a factor of two to eight times, depending on geometry. In terms of torque requirement, the torsional case is preferable.

It was expected that the in-line motor placement would have a higher torque value than the torsional motor placement for two reasons. First, the in-line motor uses a short lever arm, which amplifies the required torque. The short lever arm is due to the small angle between the spring and the arm. Second, in the in-line case, the motor must pull against the spring and the point mass, whereas in the torsional case, the motor only balances the mass, because the spring balances the arm weight. It was expected that the in-line case would require a larger torque, and the results confirm this expectation.
3.6 Conclusion

Through observation of children using the WREX, it was determined that adding a power source would be desirable. Increasingly, rehabilitation robots are using series-elastic actuators, because of safety and compliance. The WREX device was modeled with both torsional and series elastic actuation. A dynamic simulation was run in order to compare the torque requirements. In the simulations, the in-line case had a higher torque requirement. Therefore, the torsional case is preferable from a torque requirement. If a device has a spring to balance gravity and series elastic actuation is desired, it would be preferable to add actuation in torsional to the gravity balancing spring instead of directly to the gravity spring, based on this study. It has also been shown that the dynamic equations of the 2 DOF WREX device with series elastic actuation can be written as a fourth order differential equation and controlled using a computed torque method.
Chapter 4
THE CONTROL OF SERIES ELASTIC ACTUATORS

4.1 Dynamic Equations

A series elastic actuator is used to create softness for the user as well as achieve accurate torque control. A torsion spring is the elastic member that connects the motor to the device, which is show in Fig. (14).

Figure 14: Schematic of Series Elastic Actuator
The equation of motion for the motor is:

\[
\tau_m = J_m \ddot{\theta}_m + B_m \dot{\theta}_m + K_s (\theta_L - \theta_m) \tag{31}
\]

where \(\tau_m\) is the motor torque, \(\theta_m\) is the motor angle, \(\theta_L\) is the load angle, \(K_s\) is the spring stiffness and \(J_m\) and \(B_m\) are the effective motor inertia and damping, which include the gear ration. In this section, \(\theta_L\) is held constant and is considered a disturbance.

### 4.2 Control

The control method uses a PI controller with velocity feedback, similar to the control suggested by Wyeth [15], with an additional feed-forward term. This feed-forward term is equal to the desired torque output. In an ideal model, this term should cause the output torque to be equal to the input motor torque in steady state conditions. To compensate for dynamics, model uncertainty, and friction, The PI loop corrects errors in the desired torque, while the velocity feedback increases the damping, to allow the gains of the PI control to be sufficiently high to produce accurate torque control while maintaining stability. The block diagram of the control architecture is show in Fig. (15).

![Figure 15: Block Diagram of Torque Control](image-url)
4.3 Simulation and Experimentation

The control method was tested in Simulink as well as in experiment using xPC in Matlab. The experimental setup is shown in Fig. (16). The motor is a FaulHaber brushed DC motor type 2343 S 012 CR with a 134:1 gear head. The motor is powered using an Advanced Motion Control 12A8 amplifier. A US Digital E4P Optical encoder recorded the motor joint angle. The device was connected to a target PC through a NI PCI-6040E and a NI-6601 DAQ board. It was controlled at 1000Hz in realtime by Matlab xPC.

Several physical parameters were determined experimentally, \( J_m = 0.01 \, kgm^2 \), \( B_m = 0.21 \, Nm/(rad/s) \), and \( K_s = 2.51 \, Nm/rad \). The gains were determined experimentally as \( K_p = 30 \) and \( K_i = 10 \) for the outer PI control and \( K_v = 1.2 \) for the velocity feedback. First the step response was found, which is shown in Fig. (17). Second, the frequency response was determined using a chirp signal. The
experimental results were fitted to a transfer function using the system identification toolbox in Matlab. The results are shown in Fig. (18).

Figure 17: Step Response of Control on Series Elastic Actuator
From the step response, the experimental controller has a settling time of approximately 0.15 seconds with minimal steady state error. From the frequency response in Fig. (18), the controller has a bandwidth of about 20 rad/s. There is a slight discontinuity shown in the experimental response around 20 rad/s because the response was fitted in two parts, which overlap, to accurately characterize the motor non-linearities. In both figures, the difference between the simulated and experimental response is due to unmodeled time delay and motor saturation. It has been shown that the controller provides reasonable torque control up to 20 rad/s or 3.18 Hz in the absence of disturbance. This is acceptable for human interaction, because the
frequency range of a person with a disability will be substantially lower than the normal human motion of 4-8 Hz [16]. The same equipment was used as before in addition to an ATI 25.50 Mini six axis Force/Torque Sensor (ATI Industrial Automation, Apex, NC). This was used as a two axis force sensor. Motors were attached to the WREX through a torsional spring shown in Fig. (16).

4.4  Discussion

Based on the needs of the current WREX, it was decided to add a series elastic actuator to provide a soft feel for the user and allow torque control. However, the added flexibility introduced new control challenges. The presented PI controller with velocity feedback was found to provide accurate torque control in the presence of disturbances within the bandwidth needed for human motion. The controller reduces the series elastic actuator as a torque source, which any type of controller, such as PD, computed torque, or impedance could be used as a higher level control. The controller is similar to those presented by Pratt, Wyeth, and Vallery,[11, 15, 17]. Further research could implement these previously suggested strategies on the WREX and compare if one controller provides more accurate control than the other. Now that the WREX has an accurate torque source, a higher level controller can be implemented to control the interaction between the user and the device. This higher level controller will address the two mentioned problems of limited range and limited carrying ability, as well as stability.

There are position singularities where the WREX is incapable of producing a force in a certain direction. In one singularity, the WREX cannot produce a force in the horizontal direction when the device itself is horizontal with $\theta_1 = \theta_2 = 90^\circ$. 

30
Another singularity occurs in the vertical direction, however, this is outside the workspace of the WREX. The singularity in the horizontal direction does not create instability because there is no division by zero in the transpose of the Jacobian.
Chapter 5

QUANTIFYING ANTI-GRAVITY TORQUES FOR THE DESIGN OF A POWERED EXOSKELETON

5.1 Introduction

When designing devices that physically interact with humans, it is often necessary to have a model of the human to properly regulate the desired interaction. It is beneficial if the model of the human can be scaled between users based on simple measurements such as height and weight, because it can be time intensive to measure all of the properties for each subject. When the subjects have limited strength, as in this study, the model needs to be accurate enough to be used to detect the user’s intention. This paper investigates the biomechanics of a subset of pediatric patients with limited strength, to determine if a generic model can be constructed for the use in a powered upper extremity orthosis that assists people with muscular weakness to perform activities of daily living. A passive arm exoskeleton has already been developed and commercialized by this group [1, 12]. The device is called the Wilmington Robotic Exoskeleton (WREX), which is a gravity-balanced upper limb orthosis for children with muscular weakness present in conditions such as muscular dystrophy (MD) and spinal muscular atrophy (SMA). The WREX has four degrees of freedom to allow full range of motion and is assisted by gravity-balancing elastic bands [18]. The WREX can be attached to a wheelchair or to a body jacket. A picture of a currently passive WREX is shown in Fig. (19).
The WREX is designed to counterbalance the gravitational load of the arm. Hitherto, the arm was assumed to be simple rods with pinned joints and negligible joint resistance. The current study was undertaken to determine how accurate that assumption is. What are the passive forces in the sagittal plane for people with neuromuscular disabilities and how different are they from those of people without disabilities? This information will determine exactly how much contribution from a powered exoskeleton is required. Of particular importance is the proper characterization of the passive joint torques at the human elbow and shoulder.

Much work has been done to model the human upper arm [19-21]. In particular, several studies have created models for humans interacting with exoskeletons [22, 23]. However, these models are for normal subjects and do not account for altered biomechanics of people with neuromuscular disease. This paper summarizes a series of experiments to measure the passive static joint torques and maximum active joint torques a person with a disability can apply through the range of
vertical motion. Some work in modeling various disabilities, particularly those of interest to this study, namely SMA, arthrogryposis, and MD, was completed previously. Modeling has been done on the shoulder of patients with tetraplegia [24]. Work has been done on elbow joint properties in Duchenne muscular dystrophy [25], as well as investigating electromyographic activity as it relates to upper limb movement in MD [26]. One group investigated the differences in gait between patients with SMA and MD [27]. Sunnegardh et al. investigated the strength of normal children aged 8 and 13 [28]. Mathur et al. studied the time-dependent linear decrease in muscular strength of subjects with Duchenne muscular dystrophy [29]. However, the results of these studies are not sufficient to model a subject for control of an upper limb exoskeleton. Therefore, this study was conducted to obtain a preliminary understanding of differences between upper limb properties between adults, healthy children, and children with SMA, arthrogryposis, and MD. The end goal is to obtain a robust model that can be used to control a powered assistive device. The controller proposed for our powered orthosis uses residual force input from the user as a measure of his or her intention. The force sensor measures the gravitational load as well as the voluntary force of the user. The ratio of voluntary to gravitation force is very small for weak individuals; therefore, it becomes important to accurately characterize the passive forces (gravitational and passive joint resistances) to better measure the voluntary component. The anthropomorphic model used in this study is based on a person’s height and weight and only applies to people without disabilities [16]. Once a general pattern of passive joint torques for people with neuromuscular disabilities is determined, it can be used to modify the torques derived from anthropometry.
5.2 Joint Torque Measurements

5.2.1 Human Model

The initial model for the human arm was a two-link lumped mass model with pin joints shown in Fig. (20). The model was limited to the sagittal plane. The sagittal plane is the only plane where the WREX provides assistance. The other 2 joints act in the horizontal plane and are passive. Values for segment mass and center of mass were obtained from anthropomorphic tables based on the subject’s height, weight, and limb segment lengths [16]. However, initial testing showed that this model was not accurate compared with experimental values. Therefore, the shoulder and elbow joint torques in the vertical plane were measured to quantify that difference.

![Diagram of upper limb model](image)

Figure 20: Model of upper limb as two rigid links with given variables. The symbols $q_1$ and $q_2$ are the shoulder and elbow angles, $\tau_1$ and $\tau_2$ are joint torques, $m_1g$ and $m_2g$ are the gravity forces, and $F_x$, $F_y$, and $\tau_z$ are the measured forces and torque between the human and the measuring device. The force sensor is located at the origin of the force vectors.
5.3 Experimental Protocol

The procedure was approved by the Nemours Institutional Review Board. Consent forms were obtained from all subjects over the age of 18 years. Assent forms were obtained from subjects less than 18 years along with parental permission. The subjects were divided into 3 groups. Each group had 5 subjects. This institution treats patients less than 21 years of age; therefore, for the purpose of this study they are put into one group. The three groups were: 1) normal adults over the age of 21 years with no disability of the upper limb, 2) typically developing children aged 7 to 21 years with no disability of the upper limb, 3) children aged 7 to 21 years with either MD, SMA, or arthrogryposis. Table 2 summarizes the three subject categories. For each subject, several body measurements were taken, including height, weight, upper arm length, and lower arm length.

Table 2: Subject Groups

<table>
<thead>
<tr>
<th></th>
<th>Adult</th>
<th>Children</th>
<th>Children with Disabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Subjects (N)</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>25–50</td>
<td>13–19</td>
<td>13–18</td>
</tr>
<tr>
<td>Condition</td>
<td>Normal</td>
<td>Normal</td>
<td>SMA, MD, Arthrogryposis</td>
</tr>
</tbody>
</table>

The measuring device is shown in Fig. (21). It has two adjustable links with lockable shoulder and elbow joints in 20-degree increments. An arm trough is connected to a 6-axis force/torque sensor (ATI, Apex, NC). Only the 2 force directions and 1 moment direction that act in the vertical plane were recorded. A wrist splint attaches the subject’s arm to the device.
Figure 21: Measuring device with lockable joints at the shoulder and elbow with a force sensor attached to the arm trough. The subjects forearm is strapped to the arm trough and locked at various positions.

The measuring device was adjusted to fit the subject, who sat in a chair or in a powered wheelchair. The subject’s forearm was attached to the trough using a wrist splint with Velcro straps. The subject’s dominant arm was used in the experiment, since the WREX is typically used on this side. The device was locked at a maximum of 9 shoulder joint positions from 10 to 150 degrees from the vertical in 20-degree increments and 8 elbow joint positions from 0 to 140 degrees relative to the upper arm in 20-degree increments. This gives a total of 72 arm postures. For subjects with disabilities, the number of postures was reduced to remain within the comfortable range of the subject. At each position, a reading from the force sensor was taken. This reading included two forces along the x and y axis and a moment about the z axis. The subject was instructed to relax to prevent misreadings from voluntary muscle activation and was reminded to relax periodically throughout the experiment.

The measured force was transformed into joint torques at the shoulder and elbow using the Jacobian transform:
\[
\begin{bmatrix}
\tau_{\text{shoulder}} \\
\tau_{\text{elbow}}
\end{bmatrix} =
\begin{bmatrix}
\alpha_1 \sin(q_2) & a_2 + \alpha_1 \cos(q_2) & 1 \\
0 & a_2 & 1
\end{bmatrix}
\begin{bmatrix}
F_x \\
F_y \\
\tau_z
\end{bmatrix}
\] (32)

Where \( \alpha_1 \) is the length of the upper arm and \( a_2 \) is the length from the elbow to the force sensor.

For the gravitational torques of normal adults, children, and disabled subjects, the joint torques were normalized by dividing a subject’s torques by the product of the subject’s weight (N) and arm length (m):

\[
\tau_{\text{normalized}} = \frac{\tau_{\text{measured}}}{\text{weight} \times \text{arm length}}
\] (33)

A third-degree polynomial was fit to the normalized data for both the adults and healthy children:

\[
\tau(q_1, q_2) = p_{00} + p_{10}q_1 + p_{01}q_2 + p_{20}q_1^2 + p_{11}q_1q_2 + p_{02}q_2^2 + p_{30}q_1^3 \\
+ p_{21}q_1^2q_2 + p_{12}q_1q_2^2 + p_{03}q_2^3
\] (34)

where \( \tau \) is the normalized torque fit to the data, \( q_1 \) is the shoulder angle and \( q_2 \) is the elbow angle in degrees. For each subject, there are two equations. One is for the shoulder and one is for the elbow. The units are dimensionless.

It was also desirable to obtain a map of each disabled subject’s maximum upper arm strength throughout the measured range of motion. At each position, the subject with disability was asked to maximally push and pull against the force sensor, while the arm was locked. The direction of push and pull was orthogonal to the force sensor, indicated as the y-axis in Fig. (21). By both pushing and pulling in the y-axis
direction, both a negative and positive joint torque would be required, providing a window for each subject’s active joint torque strength. For both pushing and pulling, a reading in the sagittal plane was taken from the force sensor. The subjects were given several seconds to rest between readings as the arm position was adjusted to prevent effects of fatigue. The forces obtained while the subject was contracting were transformed into joint torques in the same manner that the passive forces were processed. The passive gravity torques obtained in this study were subtracted from the total applied torques for each position, resulting in the net active torques applied by the human. The net applied torques were sorted into maximum and minimum values and plotted.

5.4 Results

The full range of data for adults, typical children, and both groups combined are shown in Fig. (22). A two-dimensional slice of the data is shown in Fig. (23). The left column is the average normalized shoulder torque with the elbow in full extension. The right column is the average normalized elbow torque with the shoulder fixed at 90° from the vertical. The standard deviation is shown in error bars.
Figure 22: Average joint torques normalized to subjects’ weight and arm length. The arm figures in the upper left graph represent the arm configuration of each section of the graph. The left column is for the shoulder and the right column is for the elbow. The top two graphs are for adults, middle two for children, and bottom two for both groups combined. The dots are data points. The surface is the best fit polynomial.
Figure 23: Cross section of average joint torques normalized to subjects’ weight and arm length. Left column is with the elbow locked at zero degrees. The right column is with the shoulder locked at ninety degrees. The arm figures provide visual representation of the arm orientation. The grey line is the torque expected from the two link lump mass model.
The coefficients of the fitted polynomial in (1) for each non-disabled group for the shoulder and elbow joint are shown in Table 2. The passive gravity data of children with disabilities are shown in Fig. (24). The values were normalized to the individual’s mass and arm length; however, the values were not averaged because of the heterogeneity of the population. A cross section of the passive gravity data is shown in Fig. (25), which also contains the average of typical children for comparison, shown in solid grey. The applied torque data of children with disabilities are shown in Fig. (26). The maximum positive torque is the light surface on top. The maximum negative torque is the dark surface on the bottom. The surfaces between data points are included to help visualization; however, no curve fitting was completed. Table 3 provides a summary of both shoulder and elbow joint ranges, and maximum voluntary shoulder and elbow joint torques applied by the subject in both directions.
Table 3: Coefficients for the best-fit, third-degree polynomial of normalized joint torques

<table>
<thead>
<tr>
<th></th>
<th>Adult Shoulder</th>
<th>Adult Elbow</th>
<th>Typical Children Shoulder</th>
<th>Typical Children Elbow</th>
<th>All Typical Shoulder</th>
<th>All Typical Elbow</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{00}$</td>
<td>$-0.000992$</td>
<td>$-0.00401$</td>
<td>$-0.00420$</td>
<td>$-0.000513$</td>
<td>$-0.00259$</td>
<td>$-0.00226$</td>
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<tr>
<td>$p_{10}$</td>
<td>$0.000510$</td>
<td>$0.000149$</td>
<td>$0.000467$</td>
<td>$4.41 \times 10^{-5}$</td>
<td>$0.000488$</td>
<td>$9.66 \times 10^{-5}$</td>
</tr>
<tr>
<td>$p_{01}$</td>
<td>$0.000128$</td>
<td>$0.000314$</td>
<td>$0.000219$</td>
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<td>$0.000173$</td>
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</tr>
<tr>
<td>$p_{20}$</td>
<td>$-3.43 \times 10^{-5}$</td>
<td>$-1.08 \times 10^{-5}$</td>
<td>$-2.67 \times 10^{-6}$</td>
<td>$-1.41 \times 10^{-5}$</td>
<td>$-3.05 \times 10^{-6}$</td>
<td>$-6.13 \times 10^{-7}$</td>
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<td>$-6.55 \times 10^{-10}$</td>
<td>$1.19 \times 10^{-8}$</td>
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<tr>
<td>$p_{12}$</td>
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<td>$8.83 \times 10^{-9}$</td>
<td>$3.66 \times 10^{-10}$</td>
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<td>$p_{03}$</td>
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<td>$1.00 \times 10^{-8}$</td>
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<td>$3.57 \times 10^{-10}$</td>
<td>$5.05 \times 10^{-8}$</td>
<td>$6.82 \times 10^{-9}$</td>
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Table 4: Joint ranges, maximum applied joint torques, and average torques for children with disabilities

<table>
<thead>
<tr>
<th>Subject</th>
<th>Condition</th>
<th>Age</th>
<th>Shoulder Range(deg)</th>
<th>Elbow Range(deg)</th>
<th>Max Shoulder Torque(N/m) [up/down]</th>
<th>Max Elbow Torque(N/m) [up/down]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SMA</td>
<td>16</td>
<td>70 - 130</td>
<td>0 - 80</td>
<td>0.13 / 0.43</td>
<td>0.50 / 0.37</td>
</tr>
<tr>
<td>2</td>
<td>Arthrogryposis</td>
<td>13</td>
<td>50 - 110</td>
<td>0 - 80</td>
<td>12.7 / 9.71</td>
<td>0.72 / 3.95</td>
</tr>
<tr>
<td>3</td>
<td>MD</td>
<td>18</td>
<td>50 - 110</td>
<td>60 - 140</td>
<td>1.68 / 1.08</td>
<td>1.34 / 1.69</td>
</tr>
<tr>
<td>4</td>
<td>MD</td>
<td>14</td>
<td>50 - 150</td>
<td>0 - 140</td>
<td>2.76 / 1.94</td>
<td>2.14 / 1.38</td>
</tr>
<tr>
<td>5</td>
<td>MD</td>
<td>19</td>
<td>50 - 110</td>
<td>0 - 100</td>
<td>1.41 / 0.63</td>
<td>0.66 / 1.02</td>
</tr>
</tbody>
</table>
Figure 24: Normalized joint torques due to gravity of children with disabilities. For each subject the top graph is for the shoulder and the bottom graph is for the elbow.
Figure 25: Cross section of passive joint torques normalized to subjects’ weight and arm length. The typical children are averaged and shown as a solid line. Each disabled child is shown separately and subject number corresponds to Table 3.
Figure 26: Maximum applied torque data of children with disabilities. The upper surface is for contracting the arm upwards. The lower surface is for extending the arm downwards.
5.5 Discussion

For all subjects, the joint torques, as seen in Fig. (23), appear to follow a general pattern similar to a two-link lumped mass model, which is shown as the grey line. This demonstrates that gravity is the dominant component of passive joint torque. However, the elbow curves have the largest deviation from the model curve closer to the joint limits, which reflects increasing joint stiffness. This can be seen for an elbow angle of $0^\circ$ and $140^\circ$ in the elbow torque graph of Fig. (23). This is not seen in the graphs for the shoulder, because the measurement device was unable to reach the extreme range of motion of the shoulder. Therefore, the effects of joint stiffness on the shoulder were not as pronounced in this data. From Fig. (22), it can be seen that a third-order polynomial fits the data, and the coefficients for both adults and children have a similar relative magnitude between groups and follow a descending pattern for higher terms. These curves could be used for biomechanical studies and controlling exoskeleton strength amplifiers. To estimate the passive joint torques for a specific individual, the polynomial could be multiplied by the individual’s weight and arm length.

For all five disabled subjects, the torque curves as shown in Fig. (25), also exhibited patterns similar to a two-link lumped mass model, indicating gravity is the major component for subjects with disabilities, as well. One thing to note is that all of the subjects with disabilities had a lower range of motion than typically developing children. The 14 year old subject with MD had the greatest range of motion, followed by the subject with arthrogryposis. The other subjects with MD and the subject with SMA had the smallest range. The effects of joint stiffness were much larger than those of typical children and these effects became more noticeable closer to the neutral position in the disabled group. Also, a majority of the curves are above typically
developing children, because many of the subjects had MD and had significantly higher mass on their arms than the group of average children. There are significant differences between different disabilities as seen when comparing different subjects in Figs. (24) and (25), even though all the subjects were users or potential users of the WREX. Even within the MD group, there were significant differences between the different subjects. Since this study was limited to 3 subjects with MD, it may be possible to determine a pattern for studying a larger group that also considers the progression. A pattern was not discerned from the current study. The passive range of motion of some of the disabled subjects was limited. This prevented us from averaging all the data sets between subjects. This suggests that a subject-specific model will be needed for controlling the powered exoskeleton.

All of the subjects had an absolute maximum applied joint torque of less than 13 $Nm$ for the shoulder joint and 4 $Nm$ for the elbow joint. The maximum applied torque was less than the measured passive gravity torque for each subject, which provides a quantitative estimate of how much assistance these subjects need in upper limb motion. When curling a 17 kg weight, the human can generate on the order of 80 $Nm$ at the elbow, which is far greater than what was measured in the subjects. There was no discernible pattern or shape within or between subjects. As a note, the subjects with the highest maximum applied joint torques were observed to have the greatest upper limb function.

5.6 Conclusion

In forming a model of a human arm, measurements of the passive joint torques in the sagittal plane showed that a two-link model is inadequate to describe the human
arm. It was found that normal adults and children have a similar shape in torque differences that can be represented by a third-degree polynomial. The children with disabilities in this study did not have similar curves and could not be averaged across disabilities. A subject-specific model is suggested. It was also found that the disabled subjects’ maximum applied joint torques were lower than the passive gravity torques throughout the measured joint space and were on the order of 5% of normal voluntary torque.
6.1 Physical Design

The powered WREX project added motors to the initially passive WREX design. The powered WREX was mounted to a frame with the ability to adjust the height for each subject. A Maxon RE40 motor with a 113:1 gear ratio and encoder was attached at the shoulder and a Maxon RE30 motor with a 111:1 gear ratio and encoder was attached at the elbow. Both of these motors acted in the vertical plane. The motors were powered using two Advanced Motion Control 12A8 amplifiers. Two US Digital E4P Optical encoders recorded the horizontal shoulder and elbow joint angles. The device was connected to a target PC through a NI PCI-6040E and a NI-6601 DAQ board and controlled in realtime by Matlab xPC running at 100 Hz. An ATI 25.50 Mini six axis Force/Torque Sensor (ATI Industrial Automation, Apex, NC) was attached between the WREX and the trough for the forearm. Only the two force directions and one moment direction that act in the vertical plane were recorded. The recorded sensor data was transformed into joint torques using equation (32).

For safety, two kill switches were installed. One switch was for the patient to use and the other for an observer. In addition, physical joint stops prevented movement beyond the patient’s available range of motion. Finally, joint limits and torque limits were programmed to prevent hyperextension or flexion of the shoulder and the elbow.
6.2 Control Laws

First, a model of the user is obtained, as described in Chapter 5. The model is then used in the controller to determine the intention of the user and apply appropriate assistance to the user. The control laws determine the intention of the user by calculating the muscle torque applied by the subject at the elbow and shoulder in the vertical plane. The torque is estimated by the following equation:

$$\begin{bmatrix}
\tau_{\text{shoulder, applied}} \\
\tau_{\text{elbow, applied}}
\end{bmatrix} = \begin{bmatrix}
\tau_{\text{shoulder, measured}} \\
\tau_{\text{elbow, measured}}
\end{bmatrix} - \begin{bmatrix}
\tau_{\text{shoulder, model}} \\
\tau_{\text{elbow, model}}
\end{bmatrix}$$  \quad (35)

The following substitution will be used in further equations,

$$\tau_{\text{applied}} = \begin{bmatrix}
\tau_{\text{shoulder, applied}} \\
\tau_{\text{elbow, applied}}
\end{bmatrix}$$  \quad (36)
Three different control strategies were designed:

1. Frictionless
2. Motor torque proportional to $\tau_{applied}$
3. Motor velocity proportional to $\tau_{applied}$

6.2.1 Frictionless

The frictionless controller was used to mimic a passive WREX without motors, as a baseline to compare to the active controllers. This controller sent motor commands to feed-forward the friction from the motors. The friction constant was determined experimentally for each motor prior to being attached to the device.

6.2.2 Motor torque proportional to $\tau_{applied}$

The motor torque proportional to $\tau_{applied}$ used the following control law:

$$\tau_{motor} = k \times \tau_{applied}$$ (37)

This control law is called Torque2Torque (T2T). The concept behind this control law is that the user is controlling the amount of desired torque at each joint. The controller detects this applied torque by the human and then supplements part of the desired torque. The desired result is less torque for the user for the same motion. The value of $k$ was determined experimentally by trial and error to balance the stability and response of the controller.
6.2.3 Motor velocity proportional to $\tau_{applied}$

The motor velocity proportional to $\tau_{applied}$ used the following control law:

$$\omega_{motor} = k \times \tau_{applied}$$  (38)

This control law is called Torque2Velocity (T2V). The concept behind this control law is that the user is trying to control the angular velocity at each joint torque to move in a desired direction. The controller detects muscle activation, which causes a torque at the joints. This joint torque is then scaled to a desired velocity. Zero joint torque indicates zero desired velocity, and a larger torque indicates a larger desired velocity. The results of testing the three control laws are described in the following section.

6.3 Test Results
6.3.1 Biomechanic Model

A case study was completed with one participant, who was female, aged 15 with arthrogryposis. The participant had used the commercialized passive WREX for over 5 years. As described previously, a biomechanic model of the participant was first determined. To do so, the Powered WREX held the participant’s upper-limb at a standardized series of positions throughout her elbow and shoulder ranges of motion (see Table 5). The participant was instructed to allow complete passive movement of her limb throughout the whole procedure. At each position the force and torque between the user and WREX was measured. These data were converted into a series of measured passive shoulder joint torques and elbow joint torques. The joint torque data is shown in Table 5.
### Table 5: Joint Torque Data

<table>
<thead>
<tr>
<th>Combined Shoulder and Elbow Position</th>
<th>Shoulder Angle (rad)</th>
<th>Elbow Angle (rad)</th>
<th>Measured Shoulder Torque (Nm)</th>
<th>Measured Elbow Torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Joint Torques per Position</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.53</td>
<td>0.72</td>
<td>-2.11</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>0.53</td>
<td>1.18</td>
<td>-2.28</td>
<td>-0.81</td>
<td></td>
</tr>
<tr>
<td>0.53</td>
<td>1.55</td>
<td>-2.45</td>
<td>-0.95</td>
<td></td>
</tr>
<tr>
<td>0.53</td>
<td>1.89</td>
<td>-2.19</td>
<td>-0.94</td>
<td></td>
</tr>
<tr>
<td>0.53</td>
<td>2.24</td>
<td>-2.23</td>
<td>-0.94</td>
<td></td>
</tr>
<tr>
<td>0.73</td>
<td>1.02</td>
<td>-3.00</td>
<td>-0.37</td>
<td></td>
</tr>
<tr>
<td>0.83</td>
<td>1.11</td>
<td>-3.29</td>
<td>-0.54</td>
<td></td>
</tr>
<tr>
<td>0.89</td>
<td>1.51</td>
<td>-3.47</td>
<td>-0.85</td>
<td></td>
</tr>
<tr>
<td>0.90</td>
<td>1.87</td>
<td>-3.38</td>
<td>-0.88</td>
<td></td>
</tr>
<tr>
<td>0.90</td>
<td>2.20</td>
<td>-3.28</td>
<td>-0.90</td>
<td></td>
</tr>
<tr>
<td>1.18</td>
<td>1.48</td>
<td>-3.56</td>
<td>-0.45</td>
<td></td>
</tr>
<tr>
<td>1.21</td>
<td>1.48</td>
<td>-3.75</td>
<td>-0.63</td>
<td></td>
</tr>
<tr>
<td>1.25</td>
<td>1.84</td>
<td>-3.80</td>
<td>-0.87</td>
<td></td>
</tr>
<tr>
<td>1.25</td>
<td>2.20</td>
<td>-3.77</td>
<td>-0.90</td>
<td></td>
</tr>
<tr>
<td>1.53</td>
<td>1.61</td>
<td>-3.75</td>
<td>-0.35</td>
<td></td>
</tr>
<tr>
<td>1.61</td>
<td>1.90</td>
<td>-3.72</td>
<td>-0.79</td>
<td></td>
</tr>
</tbody>
</table>
The joint and torque data from Table 5 was curve fit to a polynomial as described in Chapter 5. The coefficients are shown in Table 6.

Table 6: Polynomial Coefficients of Curve Fit for Joint Torque Data

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Shoulder Joint Values</th>
<th>Elbow Joint Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{00}$</td>
<td>4.95</td>
<td>6.33</td>
</tr>
<tr>
<td>$p_{10}$</td>
<td>-29.30</td>
<td>0.44</td>
</tr>
<tr>
<td>$p_{01}$</td>
<td>4.42</td>
<td>-16.94</td>
</tr>
<tr>
<td>$p_{20}$</td>
<td>2.44</td>
<td>-4.80</td>
</tr>
<tr>
<td>$p_{11}$</td>
<td>39.21</td>
<td>7.83</td>
</tr>
<tr>
<td>$p_{02}$</td>
<td>-16.96</td>
<td>12.11</td>
</tr>
<tr>
<td>$p_{30}$</td>
<td>-7.93</td>
<td>1.34</td>
</tr>
<tr>
<td>$p_{21}$</td>
<td>15.13</td>
<td>3.29</td>
</tr>
<tr>
<td>$p_{12}$</td>
<td>-30.47</td>
<td>-7.48</td>
</tr>
<tr>
<td>$p_{03}$</td>
<td>12.72</td>
<td>-3.15</td>
</tr>
</tbody>
</table>
The data and curve fitting for the passive joint torque at the shoulder and elbow is shown in Fig. (28).

Figure 28: Data and curve fit of passive joint torques at the shoulder and elbow.

6.3.2 Test Methods

The biomechanic model obtained in Section 6.3 was used in the control laws described in Section 6.2. Two outcome measures were used to evaluate the control laws. One was a modified portion of the Active Movement Scale, selecting the tests that are most applicable to patients sitting in a wheelchair. The following movements were included:
1. Elbow extension, gravity eliminated
2. Elbow flexion, against gravity
3. Elbow flexion, gravity eliminated
4. Shoulder abduction, against gravity
5. Shoulder flexion, against gravity

The second outcome measure was a point-to-point test. In the point-to-point test, two points were placed on a board located in front of the subject. The subject was instructed to move her fingertip between the points five (5) times, as a measure of coordination and accuracy while wearing the device. The subject repeated the Active Movement Scale and point-to-point test for each of the three different control law scenarios.

6.3.3 Test Results

Every test except “Elbow Flexion Against Gravity” was invalidated by the accidental triggering of the range of motion safety feature, which was not noticed at the time of the experiment. This safety feature was programmed to cut off the motors if the elbow goes into hyperextension. In nearly all these tests, the elbow was in slight hyperextension, which turned off the motors during the test. The motor effort is zero for a majority of the experiment, rendering these results invalid. Since the motors provided no assistance, the motors acted as resistance rendering poor results. The test results should be repeated, making sure that the motors stay activated during the entire test. The test results that are valid are shown in the following graphs.
Figure 29: Elbow Flexion Against Gravity with Friction Compensation

Figure 30: Elbow Flexion Against Gravity with Torque2Torque
Figure 31: Elbow Flexion Against Gravity with Torque2Velocity

The test for Elbow Flexion Against Gravity was valid and is discussed below. The relevant data is combined onto the same graphs for comparison between control laws in Figs. (32) and (33).
Figure 32: Elbow Flexion Against Gravity with joint angle and motor torques
Figure 33: Elbow Flexion Against Gravity with joint angle and human torque
The elbow range of motion is the same in all three control cases. It appears that the test with friction compensation is completed faster; however there was no marker in the data to reference the start of the motion. In the bottom graph in Fig. (33), the estimated human applied torque at the elbow is mostly positive from the beginning of motion at 0.5 sec to the end of motion between 2-3 sec. All three control schemes are correctly identifying the direction of human UE movement intent. However, there is no clear difference in magnitude of human applied effort between the three control schemes. At the shoulder joint, human effort is highest for T2T, second highest for T2V, and lowest for friction compensation. However, this difference in shoulder torques is inconclusive because the shoulder is supposed to be held stationary during this test.

The Active Movement Scale was also used on the results for Elbow Flexion Against Gravity. The score is shown in Table 7.

Table 7: Active Movement Scale

<table>
<thead>
<tr>
<th>Control Scheme</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction Compensation</td>
<td>7</td>
</tr>
<tr>
<td>T2T</td>
<td>7</td>
</tr>
<tr>
<td>T2V</td>
<td>7</td>
</tr>
</tbody>
</table>

There was no difference in AMS score between the three control schemes, as evidenced by the fact that the user had full range of motion in all three control cases (indicated by score of 7, per AMS scoring values). In the “Elbow Flexion Against Gravity” test, it appears the control laws are able to correctly detect the direction of
intended motion, however there is no clear difference in magnitude between the three cases. In summary, for this particular case study, none of the control schemes were superior in producing assistance in elbow flexion. Further testing requirements are discussed in the next section.
Chapter 7

CONCLUSION AND FUTURE WORK

There are several conclusions from this work. First, use of a series elastic actuator may not be needed in upper limb orthoses for children. The series elastic actuation did not produce a noticeably more compliant interface for the user in our testing. Second, we have been able to show that the passive properties of the upper limb can be accurately modeled as a polynomial. Third, it was shown that the control laws are able to correctly predict the direction of intended motion when the device is operating within acceptable human range of motion (i.e. when safety restrictions are not triggered). Finally, there was no clear difference between the control laws in the one test that was valid. Further testing is merited to draw conclusions, however, on any differences in the control laws.

Future work should be sure that the WREX operates within normal human range of motion, such that the motors stay engaged during the testing process. Once this is accomplished, more participants should be tested to gain statistical significance and draw accurate conclusions about the control schemes. Within the larger participant population, a wider range of musculoskeletal conditions could be compared and contrasted in order to determine if the WREX is more beneficial for some conditions versus others. In addition, more advanced controllers, such as impedance, or adaptive controls could be investigated in an effort to determine the optimal user-device interface. On a practical side, the powered WREX device should be made more compact to allow for more feasible use in the home for activities of daily living. This could be accomplished by using cable driven actuation, using a portable computer for control, and making the device mountable to a wheel chair.
REFERENCES


[22] Rosen, J., Perry, J. C., Manning, N., 2005, "The human arm kinematics and
dynamics during daily activities-toward a 7 DOF upper limb powered exoskeleton,"
Advanced Robotics, 2005. ICAR'05. Proceedings., 12th International Conference on,
Anonymous IEEE, pp. 532-539.
for the Kinematical Analysis of the Joint Chain of the Human Arm," Journal of
Biomechanics, 39(13) pp. 2419-2429.
Shoulder Complex in Tetraplegia," Topics in Spinal Cord Injury Rehabilitation, 13(4)
pp. 72-85.
Properties during Elbow Flexion in Duchenne Muscular Dystrophy," The Journal of
Physiology, 533(2) pp. 605-616.
of the upper extremity in muscular dystrophy: a pilot study," Engineering in Medicine
of the IEEE, Anonymous IEEE, 2, pp. 1220-1223.
Muscular Atrophy, Type II and Duchenne Muscular Dystrophy," Gait & Posture,
21(4) pp. 369-378.
[28] Sunnegårdh, J., Bratteby, L., Nordesjö, L., 1988, "Isometric and Isokinetic
Muscle Strength, Anthropometry and Physical Activity in 8 and 13 Year Old Swedish

Appendix A

PARTICIPANT BROCHURE

BECOMING A RESEARCH VOLUNTEER:

IT'S YOUR DECISION

What Is Research?

- Research is a study that is done to answer a question.
- Scientists do research because they don't know for sure what works best to help you.
- Some other words that describe research are clinical trial, protocol, survey, or experiment.
- Research is not the same as treatment.

Why Is Research Important?

Research has led to important discoveries that make our lives better. Some examples are:

- New drugs to treat cancer, diabetes, and other diseases
- Ultrasound, X-ray machines, and diagnostic tests
- Vaccines
- Ways to stop smoking
- Improved medical procedures

Points to Consider

- A research study may or may not help you personally.
- In the future, the results could help others who have a health problem.
- Taking part in research is voluntary.

Someday, you or a family member may want to take part in a research study. If this happens, the information here may help you make the right decision.

Questions to Ask

- What exactly will happen to me in the research?
- Will there be any unpleasant side effects?
- Will the research help me personally?
- What other options do I have?
- Can I leave the study at any time?
- Will it cost me anything personally?

Research discoveries can improve people's health.

Before you decide to become a research volunteer, get the facts:

- Know what you’re getting into.
- Ask questions.
- Learn as much as you can.
- Know the pros and cons.

It's Your Decision

For more information call:

The Nemours Office of Human Subjects Protection: 904-697-4023
Toll-Free: 1-800-SOS-KIDS
Email: NOHSP@nemours.org

Office for Human Research Protections
Toll-Free (888) 447-4777
1101 Wootton Parkway
Suite 200
Rockville, MD 20852
www.hhs.gov/ohrp
Fax: (301) 402-0527
E-mail: ochp@osophs.dhhs.gov
Appendix B

INFORMED CONSENT FORM

NEMOURS
Wilmington, Delaware

INFORMED CONSENT FOR PARTICIPATION IN A RESEARCH STUDY

You have been asked to be in a research study. This form explains the research, your rights as a research participant, and any responsibilities that you may have as a result of your participation. You should understand the research study before you agree to be in it. Read this permission form carefully. You may also talk with your family or friends about it. A research team member will answer any questions you have before you make a decision.

1. WHAT IS THE TITLE OF THE STUDY?
   Human Upper Limb Parameters.

2. WHO IS IN CHARGE OF THE STUDY AT NEMOURS?
   If you have a question, complaint, or problem related to the study, you can call the investigator anytime at the numbers listed below.
   Taiga Rahman, PhD. Principal Investigator, Nemours Biomedical Research (302) 651-6931. Daniel Ragonesi, Co-Investigator, Nemours Biomedical Research, (302) 353-6605

3. WHO SHOULD RESEARCH PARTICIPANTS CONTACT ABOUT THEIR RIGHTS?
   If you have questions about your rights as a research subject, what to do if you are injured, if you would like to offer input or obtain information, or if you cannot reach the investigator or want to talk to someone else who is not involved with this research, you may contact the persons listed below.
   Carlos Rose, M.D., Chairperson, Nemours Delaware Institutional Review Board at (302) 651-5970.
   Paul Garfinkel, MSH., Director, Nemours Office for Human Subjects Protection, at (304) 807-4023.
   (Nemours Long Distance Operator) (880) SOS-KIDS (880-767-5437 )
   Website: http://www.nemours.org/research/review.html Email address: NOHSB@nemours.org

4. WHAT IS THE PURPOSE OF THE STUDY?
   The purpose of the study is to develop a better model of the upper arm, especially for kids with disabilities. This model will help in the development of a powered WREX. A powered WREX will provide greater independence for users.

5. WHO IS SPONSORING OR PAYING FOR THE STUDY?
   Nemours is the Sponsor of this study. Nemours will pay Nemours for its costs in conducting this study.

6. WHO CAN BE IN THE STUDY?
   People invited to be in this study have to meet the following criteria:
   - Are between the ages of 7 and 21
   - Are in one of the following two groups:
     - No disability of the upper body
     - or
     - Have been diagnosed with arthrogryposis, muscular dystrophy, spinal muscular atrophy

7. HOW LONG WILL PARTICIPATION IN THE STUDY LAST?
   You will be asked to come in to the Engineering Lab of the A.I. duPont Hospital for Children. We will conduct an experiment on physical properties of the upper arm. The experiment will last about 1 hr.
8. WHAT ARE THE RESEARCH PROCEDURES?
This study involves collecting data to make a model of the human arm for a WREX with motors. We will measure the height, weight, and length of the upper arm and the lower arm. If these measurements are not practical we will ask to get them from earlier medical visits. You will be placed in a device that holds his/her arm at several positions within a comfortable range. You will be asked to not move your arm. This test needs no physical effort from you. At each position a computer will quickly record the force between you and the device. There are approximately 72 positions. Each position will take only a few seconds to record.

9. WHAT ARE POSSIBLE RISKS OF BEING IN THIS STUDY?
Any research has some risks (things that could make you sick, make you feel uncomfortable, or hurt you). The risks with the most chance of happening to someone in this study are listed below. Also, there is a chance of other risks that almost never happen, or unknown risks.

Research studies often involve some risks. The subjects will be asked to put their arm in a device that holds their arm in several positions. The risks of this study are minimal. The main risk is if a part of the device breaks, however, this is very unlikely. The device is strong enough to hold several times the weight of a human arm. If a part of the device breaks, it will no longer support the subjects arm, but it will not create any additional forces on the subject. Further, a member of the research team will always be present during the experiment.

There is always a slight risk that your privacy and confidentiality may not be protected. We will ensure that any data that can be used to identify you will be well safeguarded and a code number will be used to substitute for your name. The data collected will be kept by the Principal Investigator and stored on a password protected computer. The computerized information will not be identified by name; instead a number will be assigned to subjects. This procedure is currently followed and is virtually 100% effective in maintaining confidentiality.

10. WHAT ARE POSSIBLE BENEFITS OF BEING IN THIS STUDY?
There are no likely benefits to you in participating in this study.

11. IS BEING IN THE STUDY VOLUNTARY?
Being in this study is totally voluntary. Anyone who takes part in the study can stop being in it at any time. There will be no change to your usual medical care if you decide not to be in the study or decide to stop being in the study. No one will be angry with you, or treat you any differently than before you were asked to be in the study.

You may ask the researcher to destroy your information or samples. Your request must be in writing. The researcher will tell you if this is possible.

12. WHAT ARE THE COSTS OF BEING IN THIS STUDY?
There is no cost to you for participating in this study.

13. WILL PEOPLE BE PAID FOR BEING IN THIS STUDY
You will not receive any financial benefits resulting from this study. This includes present and future payment or profit.

14. WHAT INFORMATION ABOUT ME WILL BE USED OR DISCLOSED?
Identifiable health information about you will be used by Nemours researchers and may be given to people outside of Nemours for this research. This is done to conduct the research study, to monitor...
the safety of research participants and for auditing. Federal law requires us to tell you about, and get
your approval for research use and disclosure of health information that includes "identifiers" that
can connect the health information to you. (Names, initials, date of birth, addresses, phone numbers,
and social security numbers are examples of identifiers.) This Identifiable health information is called
Protected Health Information (PHI).

Use of Health Information by Nemours Staff
The health information that will be used within Nemours includes all data collected for this study, as
described in Section 9 of this form.

Your identity will be protected as much as possible. Nemours protects your and health information
by storing records in files or computers that can only be used by authorized Nemours staff.

No protected health information identifiers, as listed above will be disclosed to persons or entities
outside of Nemours. All the identifiable information will be kept by Dr. Rahman under lock and key.
Some of the identifiable information will be kept in a computer database that will be password
protected.

The people within Nemours that may use this health information include:
- The investigators listed on the first page of this permission form and their staff,
- The Nemours Institutional Review Board (IRB) (The IRB is a group of people that reviews
  research activities. The IRB is responsible for the safety and rights of research participants),
and;
- Nemours internal audit staff.

Disclosure of Health Information to Others

Identifiable Health Information will not be disclosed outside of Nemours

Limits on Protection of Privacy and Confidentiality
Only health care organizations have to follow laws and rules about protecting the privacy of health
information. If health information containing peoples' identities is given to other kinds of companies
or organizations, they are not required by law to safeguard the privacy and confidentiality of that
information. Nemours expects these companies and organization to protect the privacy and
confidentiality of research participants, but it is not possible for Nemours researchers to assure that
this happens.

Government agencies that may look at records for this research study, including the above health
information, include:
- The U.S. Food and Drug Administration
- The U.S. Department of Health and Human Services
- Other agencies of State and local government as required by law
- Governmental agencies in other countries

The research results may be presented at scientific meetings or in print. Participants' identities will
not be disclosed in those presentations.
15. SIGNATURES:
I am making a decision whether or not to participate in this study. I have read this form, or have had it read to me in a language that I understand. I have been given enough time to make this decision. I have asked questions and received answers about things I did not understand. I willingly give consent to participate in this study. By signing this form, I am not giving up any rights to which I am entitled under law.

I understand that:
- I can withdraw permission for participation in this study and for the use and/or disclosure of PHI by contacting the person in charge of the study listed on the first page of this form.
- The use and/or disclosure of my PHI will stop after Nemours receives the withdrawal notice.
- Information that is used or disclosed before the withdrawal may still be used.
- Unless I withdraw permission, the use and/or disclosure of PHI described in this form will expire when the research study is complete and analysis and publication have ended.
- My PHI may be disclosed again by the person or organization (other than Nemours) that receives it. If this happens, Federal or state law may not protect the information.
- I have the right to refuse to sign this permission form.
- If I refuse to sign this permission form, I will not be allowed to be in this research study.
- I have the right to ask Nemours to tell me who has received my protected health information.
- I have the right to revoke my consent for the use and disclosure of my health information at any time, which would end my participation in this study.
- I will receive a signed and dated copy of this form.

My signature indicates that:
- I give my consent to participate in the research study described in this form.
- I give the researchers and Nemours permission to use and/or disclose my individually identifiable health information for this research study as described in Section 19.

<table>
<thead>
<tr>
<th>Name of Participant (Print)</th>
<th>Participant Date of Birth:</th>
</tr>
</thead>
</table>

Signature of Participant ___________________________ Date __________

I the undersigned, certify that to the best of my knowledge the participant signing this informed consent form had the study fully and carefully explained and that he/she understands the nature, risks and benefits of participation in this research study.

<table>
<thead>
<tr>
<th>Name of Person Obtaining permission (Investigator or Designee)</th>
<th>Signature of Person Obtaining permission</th>
<th>Date</th>
</tr>
</thead>
</table>

Copy of the signed form was provided to Participant on [Date] __________
Appendix C

CHILDREN ASSENT FORM AGES 7-11

Your parent has given permission for you to be in a project called a research study. But first, we want to tell you all about it so you can decide if you want to be in it. If you don’t understand, please ask questions.

What is the name of the study?
The study is called Human Upper Limb Parameters

Who is in charge of the study?
The doctor in charge of the study is Dr. Tariq Rahman with his student Daniel Regonesi.

What is the study about?
We would like to measure your arm to help make a device to help kids with weak arms.

What will happen to me in the study?
If you are in the study, here is what will happen. We will take a few of your measurements, like your height, weight, and length of your arm. Then we will ask you to put your arm in a thing that looks like your own arm. Your arm will be held still in several places. We will ask you to not move too much. It should only take about 1 hour to do everything. Your arm might get tired.

Do I have to be in the study?
You don’t have to do the study if you don’t want to. If you are in the study, you can stop being in it at any time. Nobody will be upset with you. No matter what you decide, the doctors and their helpers will take care of you just like they did before. If you have any questions or don’t like what is happening, please tell your parent, the doctor or helper.

You have had the study explained to you. You have been given a chance to ask questions. By writing your name below, you are saying that you want to be in the study.

---

Child’s Signature

Date

---

Name of Person Obtaining Ascent

Signature of Person Obtaining Ascent

Date

☐ The assent information was read to the child by the person obtaining assent
☐ The child read the assent him/herself

---

Version May 1, 2008
Appendix D

ADOLESCENT ASSENT FORM AGES 12-17

ADOLESCENT ASSENT FORM FOR YOUTH AGES 12-17

Your parent has given permission for you to be in a project called a research study. But first, we want to tell you all about it so you can decide if you want to be in it. If you don’t understand, please ask questions. You can choose to be in the study, not be in the study or take more time to decide.

What is the name of the study?
The study is called Human Upper Limb Parameters

Who is in charge of the study?
The doctor in charge of the study is Dr. Tariq Rahman with his student Daniel Ragonesi

What is the study about?
We would like to take some measurements of your arm in different positions. This will help us to make a device to help kids with weak arms.

Why are you asking me to be in this study?
You are being asked to be in the study because you either have a neuromuscular disability that prevents you from using your arm normally or you can help other kids that do. The doctor in charge of this study thinks it is important because your participation will tell us how to better design the arm device.

What will happen to me in the study?
If you are in the study, here is what will happen: We will take a few of your measurements, like your height, weight, and length of your arm. Then we will ask you to put your arm in a thing that looks like your own arm. Your arm will be held still in several places. We will ask you to not move too much. It should only take about 1 hour to do everything. You should not experience any pain. Your arm may get a little tired after the study.

Research studies often involve some risks. You will be asked to put your arm in a device that holds your arm in several positions. The risks of this study are minimal. The main risk is if a part of the device breaks, however, this is very unlikely. The device is strong enough to hold several times the weight of a human arm. If a part of the device breaks, it will no longer support your arm, but it will not push you in any way. Further, a member of the research team will always be with you during the experiment.

Will I be paid to be in this study?
You will not be paid for being in this study.
Appendix E

PARENTAL PERMISSION FORM

NEMOURS
Wilmington, Delaware

PARENTAL PERMISSION FOR PARTICIPATION IN A RESEARCH STUDY

You have been asked to permit your child to be in a research study. This form explains the research, your child's rights as a research participant, and any responsibilities that you may have as a result of your child's participation. You should understand the research study before you agree to permit your child to be in it. Read this permission form carefully. You may also talk with your family or friends about it. A research team member will answer any questions you have before you make a decision.

1. WHAT IS THE TITLE OF THE STUDY?
   Human Upper Limb Parameters.

2. WHO IS IN CHARGE OF THE STUDY AT NEMOURS?
   If you have a question, complaint, or problem related to the study, you can call the investigator anytime at the numbers listed below.
   Tanq Rahman, PhD, Principal Investigator, Nemours Biomedical Research (302) 651 6331.
   Daniel Ragoires, Co-Investigator, Nemours Biomedical Research, (302) 353 6605

3. WHO SHOULD RESEARCH PARTICIPANTS CONTACT ABOUT THEIR RIGHTS?
   If you have questions about your child's rights as a research subject, what to do if your child is injured, if you would like to offer input or obtain information, or if you cannot reach the investigator or want to talk to someone else who is not involved with this research, you may contact the persons listed below.
   Carlos Rose, M.D., Chairperson, Nemours-Delaware Institutional Review Board at (302) 651-5970.
   Paul Garfinkel, MSH, Director, Nemours Office for Human Subjects Protection, at (304) 697-4023.
   (Nemours Long Distance Operator) (800) SOS-KIDS (800-767-5437)
   Website: http://www.nemours.org/research/ohsp.html Email address: NCHSP@nemours.org

4. WHAT IS THE PURPOSE OF THE STUDY?
   The purpose of the study is to develop a better model of the upper arm, especially for kids with disabilities. This model will help in the development of a powered WREX. A powered WREX will provide greater independence for users.

5. WHO IS SPONSORING OR PAYING FOR THE STUDY?
   Nemours is the Sponsor of this study. Nemours will pay Nemours for its costs in conducting this study.

6. WHO CAN BE IN THE STUDY?
   People invited to be in this study have to meet the following criteria:
   • Are between the ages of 7 and 21
   • Are in one of the following two groups:
     o No disability of the upper body
     o Have been diagnosed with arthrogryposis, muscular dystrophy, spinal muscular atrophy

7. HOW MANY OTHER PEOPLE WILL BE IN THE STUDY?
   There will be 5 adults and 10 children in the study. Each person will be tested separately.

Page 1 of 5
8. HOW LONG WILL PARTICIPATION IN THE STUDY LAST?
Your child will be asked to come in to the Engineering Lab of the A.I. duPont Hospital for Children. We will conduct an experiment on physical properties of the upper arm. The experiment will last about 1 hr.

9. WHAT ARE THE RESEARCH PROCEDURES?
This study involves collecting data to make a model of the human arm for a WREX with motors. We will measure the height, weight, and length of the upper arm and the lower arm. If these measurements are not practical we will ask to get them from earlier medical visits. Your child will be placed in a device that holds his/her arm at several positions within a comfortable range. They will be asked to not move their arm. This test needs no physical effort from the children. At each position a computer will quickly record the force between the child and the device. There are approximately 72 positions. Each position will take only a few seconds to record.

10. WHAT ARE POSSIBLE RISKS OF BEING IN THIS STUDY?
Any research has some risks (things that could make your child sick, make your child feel uncomfortable, or hurt your child). The risks with the most chance of happening to someone in this study are listed below. Also, there is a chance of other risks that almost never happen, or unknown risks.

Research studies often involve some risks. The subjects will be asked to put their arm in a device that holds their arm in several positions. The risks of this study are minimal. The main risk is if a part of the device breaks, however, this is very unlikely. The device is strong enough to hold several times the weight of a human arm. If a part of the device breaks, it will no longer support the child’s arm, but it will not create any additional forces on the subject. Further, a member of the research team will always be present during the experiment.

There is always a slight risk that your privacy and confidentiality may not be protected. We will ensure that any data that can be used to identify your child will be well safeguarded and a code number will be used to substitute for your child’s name. The data collected will be kept by the Principal investigator and stored on a password protected computer. The computerized information will not be identified by name; instead a number will be assigned to subjects. This procedure is currently followed and is virtually 100% effective in maintaining confidentiality.

11. WHAT ARE POSSIBLE BENEFITS OF BEING IN THIS STUDY?
By participating in this study, your child will be part of a study developing a device that may directly benefit your child. It is possible, however, that no therapeutic or other direct health benefits may result during or following completion of this study.

12. WHAT HAPPENS IF A PROBLEM OR INJURY RESULTS FROM THE RESEARCH PROCEDURES?
Nemours will assure that your child receives treatment, if needed, for study related injuries. Neither Nemours nor the study doctor have a program to pay for medical care provided to treat the injury. If you have health insurance, it may, or may not pay for the cost of treatment resulting from a study-related injury. If your insurance does not pay, you understand that you will be responsible for paying for the cost of treatment.
If your insurance does not pay for study-related injury, or if you do not have insurance, you will be responsible for paying for the cost of treatment.

If you think that your child has been injured while in this study or has a problem related to the study, you should tell one of the study doctors as soon as possible. The study doctor or research staff will tell you what you should do. The study doctor’s names and phone numbers are on the first page of this form.

13. IS BEING IN THE STUDY VOLUNTARY?
Being in this study is totally voluntary. Anyone who takes part in the study can stop being in it at any time. There will be no change to your child’s usual medical care if you or your child decide not to be in the study or decide to stop being in the study. No one will be angry with you or your child, or treat your child any differently than before your child was asked to be in the study.

If you withdraw your child from this study, your child may continue treatment with his/her doctor, or you may seek treatment for your child from another doctor of your choice.

14. WHAT OPTIONS ARE AVAILABLE OTHER THAN BEING IN THIS STUDY?
Because this study does not involve a new treatment or a change in treatment for your child, the alternative is to not participate. Your decision of whether or not to participate in this study will not impact your child’s care at the Alfred I. duPont Hospital for Children in any way.

15. CAN THE RESEARCHERS REMOVE SOMEONE FROM THE STUDY?
The investigators will remove your child from the study if your child chooses to stop participating, or if you choose to stop your child from participating. All subsequent research appointments will be cancelled.

16. WHAT ARE THE COSTS OF BEING IN THIS STUDY?
There is no cost to you for participating in this study.

17. WILL PEOPLE BE PAID FOR BEING IN THIS STUDY?
You will not receive any financial benefits resulting from this study. This includes present and future payment or profit.
Your child will receive no payment for participating in this study.

18. WILL I BE TOLD OF ANY NEW INFORMATION THAT MIGHT AFFECT MY WILLINGNESS TO PERMIT MY CHILD TO STAY IN THE STUDY?
Any new information that may change your mind about allowing your child to be in this study will be given to you. A committee called the Institutional Review Board (IRB) will review this study at least once per year. If the IRB finds that there is new information that you should know about while your child is taking part in this study, it will ask the study doctor to tell you about it. You may be asked to sign a new version of this form after discussing the new information with a member of the research team.

19. WHAT INFORMATION ABOUT MY CHILD WILL BE USED OR DISCLOSED?
Identifiable health information about your child will be used by Nemours researchers and may be given to people outside of Nemours for this research. This is done to conduct the research study, to monitor the safety of research participants and for auditing. Federal law requires us to tell you about, and get your approval for research use and disclosure of health information that includes "identifiers" that can connect the health information to your child. (Names, initials, date of birth, addresses,
phone numbers, and social security numbers are examples of identifiers.) This identifiable health information is called Protected Health Information (PHI).

Use of Health Information by Nemours Staff
The health information that will be used within Nemours includes all data collected for this study, as described in Section 9 of this form.

Your child’s identity will be protected as much as possible. Nemours protects your and your child’s health information by storing records in files or computers that can only be used by authorized Nemours staff.

No protected health information identifiers, as listed above will be disclosed to persons or entities outside of Nemours. All the identifiable information will be kept by Dr. Rahman under lock and key. Some of the identifiable information will be kept in a computer database that will be password protected.

The people within Nemours that may use this health information include:
- The investigators listed on the first page of this permission form and their staff,
- The Nemours Institutional Review Board (IRB) (The IRB is a group of people that reviews research activities. The IRB is responsible for the safety and rights of research participants), and;
- Nemours internal audit staff.

Disclosure of Health Information to Others
Identifiable Health Information will not be disclosed outside of Nemours

Limits on Protection of Privacy and Confidentiality
Only health care organizations have to follow laws and rules about protecting the privacy of health information. If health information containing peoples’ identities is given to other kinds of companies or organizations, they are not required by law to safeguard the privacy and confidentiality of that information. Nemours expects these companies and organization to protect the privacy and confidentiality of research participants, but it is not possible for Nemours researchers to assure that this happens.

Government agencies that may look at records for this research study, including the above health information, include:
- The U.S. Food and Drug Administration
- The U.S. Department of Health and Human Services
- Other agencies of State and local government as required by law
- Governmental agencies in other countries

The research results may be presented at scientific meetings or in print. Participants’ identities will not be disclosed in those presentations.
20. SIGNATURES:
I am making a decision whether or not to permit my child to participate in this study. I understand that my child may also have to agree to participate in the study before he/she will be allowed to be in this study. I have read this form, or have had it read to me in a language that I understand. I have been given enough time to make this decision. I have asked questions and received answers about things I did not understand. I willingly give permission for my child to participate in this study. By signing this form, I am not giving up any rights to which I am entitled under law.

I understand that:
- I can withdraw permission for participation in this study and for the use and/or disclosure of PHI by contacting the person in charge of the study listed on the first page of this form.
- The use and/or disclosure of my child's PHI will stop after Nemours receives the withdrawal notice. Information that is used or disclosed before the withdrawal may still be used.
- Unless I withdraw permission, the use and/or disclosure of PHI described in this form will expire when the research study is complete and analysis and publication have ended.
- My child's PHI may be disclosed again by the person or organization (other than Nemours) that receives it. If this happens, Federal or state law may not protect the information.
- I have the right to refuse to sign this permission form.
- If I refuse to sign this permission form, my child will not be allowed to be in this research study.
- I have the right to ask Nemours to tell me who has received my child's protected health information.
- I have the right to revoke my permission for the use and disclosure of my child's health information at any time, which would end his/her participation in this study.
- I will receive a signed and dated copy of this form.

My signature indicates that: As his or her parent or guardian, I give my permission for the minor child named below to participate in the research study described in this Parental Permission Form.
- I give the researchers and Nemours permission to use and/or disclose my child's individually identifiable health information for this research study as described in Section 19.

Name of Participant (Print)

Participant Date of Birth:

Signature of Parent / Guardian

Printed Name of Parent / Guardian

Date

Check Relation to Participant: _Parent _ Guardian: (Guardians must have documented authority to give permission for participation in a research study according to the laws of the State in which the treatment occurs.)

I the undersigned, certify that to the best of my knowledge the parent/legal representative signing this permission had the study fully and carefully explained and that he/she understands the nature, risks and benefits of participation in this research study.

Name of Person Obtaining permission (Investigator or Designee)

Signature of Person Obtaining permission

Date

Copy of the signed form was provided to Parent/Guardian on [Date]__________