Design and Control of RUPERT: A Device for Robotic Upper Extremity Repetitive Therapy

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***Abstract*—The structural design, control system, and integrated biofeedback for a wearable exoskeletal robot for upper extremity stroke rehabilitation are presented. Assisted with clinical evaluation, designers, engineers, and scientists have built a device for robotic assisted upper extremity repetitive therapy (RUPERT). Intense, repetitive physical rehabilitation has been shown to be beneficial overcoming upper extremity deficits, but the therapy is labor intensive and expensive and difficult to evaluate quantitatively and objectively. The RUPERT is developed to provide a low cost, safe and easy-to-use, robotic-device to assist the patient and therapist to achieve more systematic therapy at home or in the clinic. The RUPERT has four actuated degrees-of-freedom driven by compliant and safe pneumatic muscles (PMs) on the shoulder, elbow, and wrist. They are programmed to actuate the device to extend the arm and move the arm in 3-D space. It is very important to note that gravity is not compensated and the daily tasks are practiced in a natural setting. Because the device is wearable and lightweight to increase portability, it can be worn standing or sitting providing therapy tasks that better mimic activities of daily living. The sensors feed back position and force information for quantitative evaluation of task performance. The device can also provide real-time, objective assessment of functional improvement. We have tested the device on stroke survivors performing two critical activities of daily living (ADL): reaching out and self feeding. The future improvement of the device involves increased degrees-of-freedom and interactive control to adapt to a user's physical conditions.**

***Index Terms*—Control, neuromotor function, pneumatic muscle, rehabilitation robot, repetitive therapy, stroke.**

I. Introduction

RECENT research has shown that neural plasticity in the brain has the capability to allow stroke survivors to recover control of motor function. Functional maps from brain imaging show that motor cortical representation shrinks with inactivity following lesions and may expand with subsequent activity [1]–[6]. These findings form the basis for new therapeutic treatments of stroke survivors and patients with traumatic brain injury: repetitive motor function activities. For example, the stroke survivor is asked to reach for a glass multiple times assisted by a therapist. The rehabilitation sessions can last for 1 h a day, multiple days a week, for many months. Although the therapy shows promise, the current approach and techniques are very labor intensive and lack consistency and objective assessments. Therapists can use standard tests to quantify improvement such as the Wolf Motor Function Test (WMFT), but it would be beneficial to collect and store data about each training session. There has been a continuous effort by engineers to develop robotic systems that can assist and improve the rehabilitation of patients with neuromuscular disabilities. A very good review of robotic devices to assist in these therapies is presented in [7]. The typical robotic systems tend to be expensive and are often developed for research purposes, and therefore, they are too complex for practical clinical use and impossible for home use. There is a need for affordable, practical, and multidimensional devices to assist the therapist in upper extremity rehabilitation. Together with clinical evaluation, designers, engineers, and scientists have built a device for robotic assisted upper extremity repetitive therapy (RUPERT). The device is designed to provide active assistance for repetitive physical therapy of the upper extremity. For example, the patient is asked to reach for a glass. The patient must attempt the task in a real world setting against gravity. If the patient cannot start or finish the task, the pneumatic muscles (PMs) will provide the required assistance for completion of the task.

One significant design specification different from most other rehabilitation robots is that the RUPERT is designed to assist the repetitive therapy of multiple, arm- movement types in a 3-D work space without gravity compensation. It is important to note that most tasks of ADL are practiced in a natural setting. It is our belief that practicing tasks in a natural environment will better translate to improved motor function in daily tasks.

Many important activities of daily living, such as grooming, dressing, and eating depend on two-handed function [8]. Since our device is designed to be wearable and portable it is easy to program the device and design therapies to assist the patient to practice coordinated bi-manual activities at clinic or at home to take full advantage of the repetitive therapy.

II. Design

The design goals are to develop an upper-extremity exoskeletal, therapeutic device that provides training of critical

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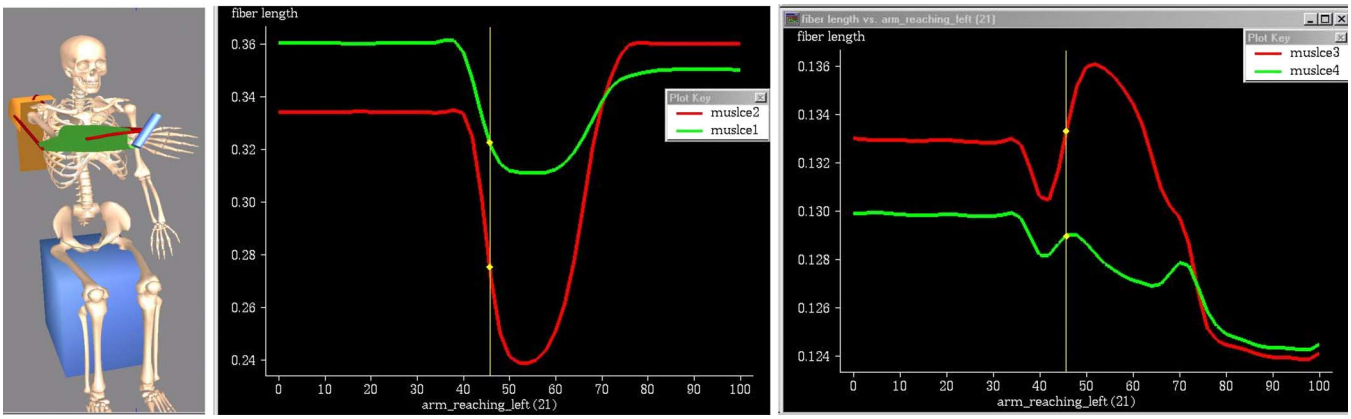

Fig. 1. SIMM model was used to assist the design of PMs for proper size, length and attachment points. Length changes of 4 PMs during simulated reaching and self-feeding activities are shown in the figure. Reaching cycle is from 0% to 100% and the fiber length is measured in meters.

reaching and feeding motions for activities of daily living. The device is compact and lightweight for portability, relatively easy to use for self donning and doffing, capable of interacting with a personal computer based biofeedback system to capture the interest of the user, and can provide adequate torque at the shoulder, elbow, and wrist during training of functional reaching and feeding tasks. The device can also provide measurement of functional performance for evaluation purposes, guiding the progress of each therapy session (see Section IV). Another requirement is to develop an inexpensive device that can assist the therapist at the clinic and can be used for supplemental in-home therapy.

The technology of the existing hand mentor air-muscle driven wrist/hand device [9] formed a starting point for the new rehabilitation robot. The team also designed a gait trainer based on pneumatic muscles as well [10]. The new device incorporates coordinated elbow and shoulder motions and provides active assistance at four degrees-of-freedom: shoulder elevation (flexion), elbow extension, forearm supination, and wrist/hand extension. Rehabilitation of the affected upper extremity thus is oriented toward restoring the normal sensorimotor relationships between the joints for actually performing activities of daily living [11].

Traditional robots are usually driven by electric motors attached to gear boxes which can be very stiff and supply very large torques which could result in injury to a stroke survivor with spasticity. Electric motor actuation in wearable robotic applications presents a mismatch in the compliance of the actuator and the limb being assisted. Impedance control of actuators has had success in addressing this problem, but adds another layer of complexity and extra cost [12], [13]. The "McKibben" type pneumatic actuators used in RUPERT provide compliant actuation and thus reduce the complexity of the control system compared to stiffer drives. They can naturally extend if a spastic response occurs during the rehabilitation task. These pneumatic muscles (PMs) have a venerable history of use in rehabilitation devices [14]–[17]. However, the compliance also presents challenges in design and control, in a different way: slower response time in force generation and the dependence of the position and movement speed on external load or resistance. Further, the dynamic range of PMs for required range of motion also depends on the anchor position and the length. We used modeling and simulation to guide the design and selection of parameters for the pneumatic muscles. To prepare for a safe and effective closed-loop feedback controller, we are investigating dynamic relationships among applied pressures, muscle sizes and material properties, and external loads.

A. Modeling

A kinematic model of the upper extremity was developed using SIMM (software for interactive musculoskeletal modeling); see Fig. 1. The model was used to study the effect of insertion/origin locations of the pneumatic muscles on the joint ranges of motion and desired limb trajectories [18]–[20]. Based on the anthropomorphic data of an average man, the required lengths of each PM to generate the desired range of motion are 0.37, 0.3, 0.14, and 0.18 m, for the shoulder, elbow, wrist, and supination, respectively.

A kinetic model of the integrated human arm with the exoskeletal robot (see Appendix) was also developed to calculate the forces required for each PM to assist the desired reaching and feeding tasks under different residual muscle forces or spastic forces in the combined system that includes the robot and subject's arm [20]. The resistance of soft tissues and possible muscle spasticity must be considered when determining the joint torques required to overcome gravity. To minimize the possibility of eliciting spasm when assisting arm movement, the air flow to the PM is currently restricted so that the joint rotation speed is limited to 25–50°/s. (depending on load), but can be increased as patient's performance or condition improves. To increase efficiency, shoulder and elbow air muscles were attached to cables that lay on cams. The cams increase the PM moment arm as elbow extension and shoulder elevation proceed. If a larger torque is required, larger diameter air muscles or higher pressures can easily be incorporated under the constraint of safety limitation.

The simulation results from the model assisted the initial design and adjustment of RUPERT. Further use of the model also allows the clinician to assess the evaluation of recovery in voluntary control by estimating the muscle torques generated by the subject (see Section IV).

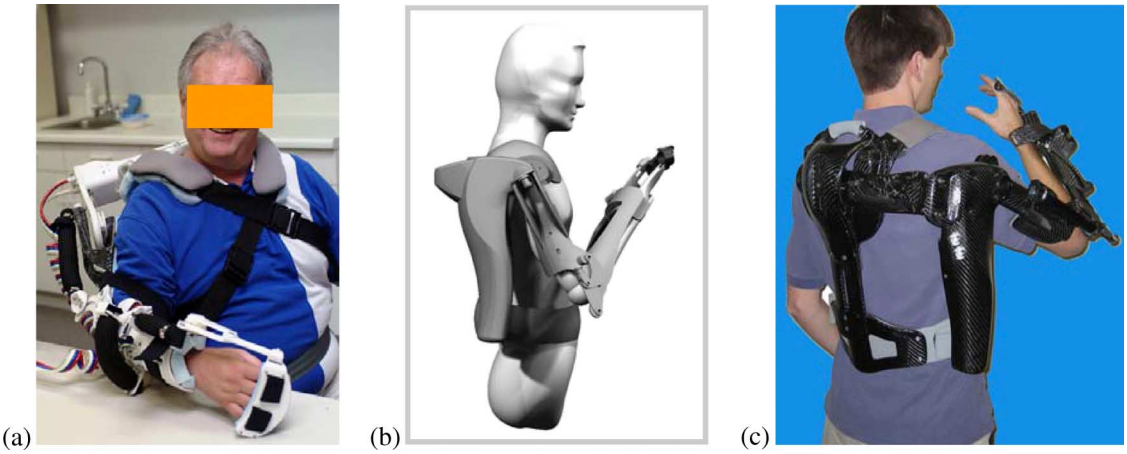

Fig. 2. Evolution from Version II to the design and construction of Version III. (a) Subject wearing Version II. (b) Computer-generated model of RUPERT Version III. (c) Latest version of RUPERT using carbon fiber composites. RUPERT is powered by four pneumatic muscles, has four actuated degrees-of-freedom (one at the shoulder, two at the elbow, and one at the wrist). Shown here is the version for the right arm. Lengths of both upper and lower arm segments can be adjusted to fit a wide range of patient body sizes. It is easy to put on and take off.

B. Structure Design

The first working mockup verified that four pneumatic muscles could achieve the desired ranges of motion as well as the trajectories needed to assist in reaching and feeding tasks. Based on the experience with the mockup, Version I was fabricated. RUPERT I included four air muscles to actuate shoulder elevation, elbow extension, supination, and wrist extension after considering stroke survivors functional conditions. The structure of this first prototype restricted the shoulder abduction to one plane (15° lateral) and limited the maximum elevation to 45°. The support structure had a pad that stabilizes the scapula.

In Version II, the center of rotation and the length for each segment are both adjustable to accommodate the variable arm lengths and builds of individual patients. The design goal is to accommodate 95% of the patient population without having to supply multiple sizes of the device. The design is more complex with this specification: multiple adjustable components add weight and demand higher mechanical strength.

The hand piece has the extension mechanism only on one side of the hand and each individual fingertip is supported rather than the total dorsal surface of the phalanges. This is done to make grasping objects easier. The linkage along side of the hand provides a coordinated opening motion of the hand into the position of function. The shoulder and elbow joints have mechanisms that increase the moment arm of the air muscle as extension and elevation increase.

Based on fitting evaluations from a range of statures of able-bodied and stroke survivor volunteers and device testing of Version I and II at Banner Good Samaritan Regional Medical Center, Version III has been developed (see Fig. 2). A composite structure was created to make the robot lightweight but still strong.

The specifications of RUPERT III are given in Table I.

TABLE I
JOINT SPECIFICATIONS OF RUPERT

Range of Motion	
Shoulder forward flexion	15 ° to 85°
Elbow flexion	125° to 0°
Supination	45° pro to 45° sup
Hand	60° flex to 30° ext
Max Torques	
Shoulder	15 NM
Elbow	15 NM
Supination	3 NM
Hand	15 NM

III. CONTROL

Fig. 3 shows the block diagram for the initial control structure. This is the open loop feedforward control for initial testing and evaluation of the suitability and safety for rehabilitation of arm reaching tasks. The final position error relies on the patient voluntary effort to correct. Advanced features for intelligent and adaptive control are under development to accommodate the progression of each patient as they improve voluntary control of reaching tasks.

Currently, the patient is asked to start a predefined movement, and if the movement is not initiated or the patient does not reach far enough, the muscles are activated. The sequence and the timing of muscle activation is calculated using the SIMM model (see Fig. 1) and custom adjusted by the therapist for each subject in this initial design. The therapist has the ability to change the amount of movement and the speed of movement according to each patient's physical condition and control ability. For example, the therapist can set the elbow to be extended 75° in 3 s or 2 s, but there is a limit on the maximum angular speed for safety consideration or spasticity. The therapist can then set the parameters for the shoulder and wrist muscles. Two tasks were programmed for patient testing, one for reaching and a second for a feeding motion (reaching out and bringing a cup to the mouth).

The pneumatic muscles are custom designed to fit the force and velocity requirements of each actuator. The shoulder muscle is much larger and stronger than the wrist muscle, for example. These muscles are activated with three-way valves. Air flow fills the muscle when assistance is needed; it releases the flow if the task is finished or it holds the air in the muscle assisting the patient to hold after reaching a target location. The current

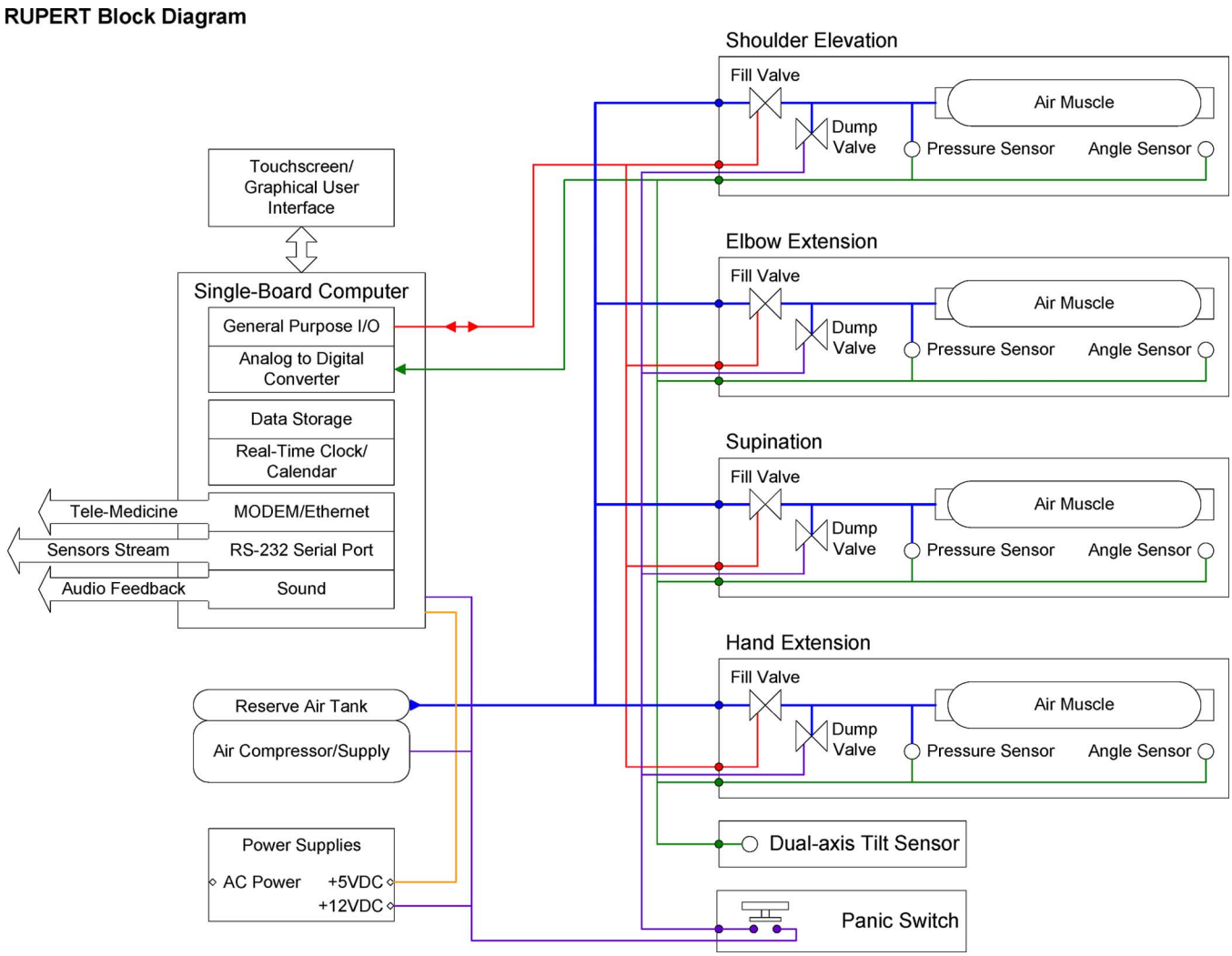

Fig. 3. Block diagram of the initial pneumatic control system for the robot. It is an open-loop feedforward control.

control will not be able to enforce a trajectory and may generate a large steady state error at the end position if the patient has a strong abnormal muscle control and lacks voluntary control ability. The objective of this design is for robot assisted repeated therapy to train the patient to improve voluntary control and reduce the error. However, for more severely impaired patients a closed-loop feedback control to train on more accurate path and position may be desirable.

Position sensors are included in the shoulder, elbow, and wrist axes as well as measuring supination. The wrist, elbow, and shoulder pots are positioned in the exoskeleton and located in-line with the physiological joint axes. These sensors measure the joint rotation directly. For measuring supination, the pot is connected to a pinion that is driven by a rack attached to a constant radius forearm structure.

T-Noble Potentiometers (Model XV094N) are used to measure all joint angles. Specifications are in Table II.

An inertial sensor is also included in the trunk fixation frame as reference for body position relative to a global coordinate frame. The inertial sensor provides two axes tilt measurement (Analog Devices ADXL320 2-axis $+/-5$ g accelerometer). Since the trunk movement from stroke survivors during the therapy is discouraged, the movement acceleration will be small compared to the gravitational effect. The measurement will be counted as tilt. The specification is listed in Table III.

TABLE II
POTENTIOMETER SPECIFICATIONS

Rated Power	0.05 w
Rated Voltage	6V
Rotational Noise	200 mV
Operating Angle	220°
Max Rotational Torque	3mNM
Endurance	1,000,000 Cycles

TABLE III
INERTIAL SENSOR SPECIFICATIONS

Output Type	Analog
TypicalBand Width (kHz)	2.5kHz
Voltage Supply (V)	2.4 to 6
Range	+/- 5g
Sensitivity	174 mV/g
# of Axes	2
Sensitivity Accuracy (%)	±10
Temp Range (°C)	-20 to 70°C
Package	CP-16
Noise Density (µg/rtHz)	250

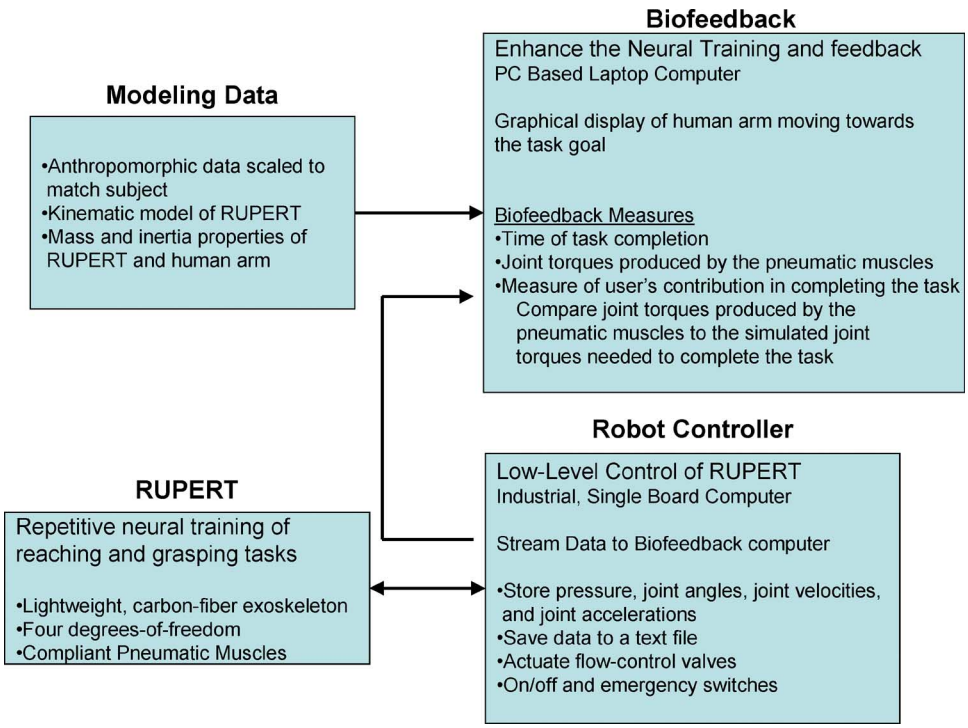

Fig. 4. Integrated biofeedback system directly interacts with the robot controller shown in Fig. 3. Pressure, joint angles, joint velocities, and joint accelerations are streamed to the biofeedback system for analysis. Anthropomorphic data and RUPERT data are used to determine the inertia and mass of each arm segment. Biofeedback system then estimates the voluntary muscle activity of each joint segment of the subject. Time of task completion is also measured. Lastly, the data is stored in a database for follow-up analysis by the clinician.

Together with the pressure sensors the information is used in the biofeedback system to determine the quality of the movement and for estimation of voluntary muscle torques from the patient in evaluation of recovery and improvement of motor function. The sensor information is sampled into the Diamond Systems SBC for RUPERT on a 12-bit ADC. These sensors are the current selection but we are investigating other choices for more accurate and durable performance and economical considerations.

IV. Biofeedback

The integrated biofeedback system in Fig. 4 directly interacts with the robot controller shown in Fig. 3. The pressure data and joint data are sent to a portable laptop for analysis. The laptop computer runs Matlab's SimMechanics which determines the joint velocities, accelerations, and inertia. The SimMechanics model uses inverse dynamics calculations to estimate the torque needed to move the combined RUPERT arm and subject's arm. The mass and inertia properties of the RUPERT arm are determined from the SolidWorks computer aided design model. The anthropomorphic data is determined by scaling a model based on the user's height and weight (see Appendix).

Once the dynamic torque is estimated for each joint by SimMechanics, then the amount of torque supplied by the PMs is determined. The torque supplied by the PM is calculated by knowing the pressure of each PM, the length of the lever arm, and the angle of each joint. The nonlinear properties of each PM are empirically measured and derived for a more accurate dynamic model for PM torque estimation.

The biofeedback system estimates the voluntary muscle activity on each joint of the subject by subtracting the estimated dynamic torque from the torque supplied by the PM. In real-time, the clinician can get an estimate of the amount of voluntary muscle activity of the patient. The goal is to reduce the pressure in the PM over time to increase the amount of work and effort of the subject during training.

The time of task completion is also measured. The goal is for the subject to finish the task in a slow but reasonable amount of time. Lastly, the data is stored in a database for follow-up statistical analysis by the clinician. In the future, subjects can use the RUPERT device at home and store data that can later be retrieved by the clinician.

V. Results

The ASU IRB approved laboratory testing on patients and the Banner IRB approved clinic testing. We performed preliminary test and evaluation of the safety, suitability and effectiveness of the RUPERT design on rehabilitation of stroke survivals through the repeated therapy protocol.

Eight able-bodied volunteers tried on RUPERT I. Each subject's limb segment and torso lengths and the associated position of RUPERT's adjustment settings were recorded. A wide range of statures was included in the volunteers from 5 ft tall females to males over 6 ft. Two stroke survivors tried on Version I and were able to move their limbs in the desired directions. Another two have completed three week therapy protocols using RUPERT I. The purpose of these tests is to evaluate the ability of the prototype to function in a clinical environment and not focus on patient results. The evaluation by the therapists and patients

Demographics

	Age (years)	Gender	Height (inches)	Weight (lbs)	Race
S-01	50	Male	75	265	Caucasian
S-02	48	Female	64	175	Caucasian
S-03	59	Male	70	270	Caucasian
S-04	50	Male	73	254	Caucasian
S-05	71	Male	68	200	Caucasian
S-06	44	Male	67	155	Caucasian
S-07	58	Male	70	190	Caucasian
S-08	54	Male	74	327	African American
S-09	44	Male	72	160	African American
S-10	63	Female	66	210	Caucasian
Mean	54.1	---	69.9	220.6	---
Range	44-71	---	64-75	155-327	---

Stroke and Impairment Severity

	Severity Classification	Time Since Stroke in months	Hemiplegia (limited by device)	Adverse Events during training
AR-01	Mild	120	Right	None
AR-02	Moderate	8	Right	none
AR-03	Mild	48	Right	None
AR-04	Moderate	3	Right	None
AR-O5	Mild	15	Right	None
AR-06	Moderate	11	Right	None
S-07	Severe	48	Right	None
S-08	Moderate	24	Right	None
S-09	Moderate	32	Right	None
S-10	Mild	18	Right	None
Mean	---	32.70	---	---
Range	---	3-120	---	---

Modified Wolf Motor Test

	Simple Tasks				**Complex Tasks**		
	Faster is better (seconds)				Faster is better (seconds)		
	Before	After	Change		Before	After	Change
AR-01	2.6	2.1	-0.5		286.6	274.7	-12
AR-02	19.4	11.3	-8.1		812.9	747.1	-65.8
AR-03	3.1	3.5	0.4		21.1	21.2	0.1
AR-04	8.6	6.9	-1.7		540.8	345.5	-195.3
AR-05	5.19	5.91	-0.72		28.64	29.71	-1.07
AR-06	250.82	16.41	-249.41		840	753	-87
Mean	48.29	7.69	-43.34		421.67	361.87	-60.18

Fig. 5. Summary of subject population and stroke severity. Wolf Motor Test was performed before and after the three week protocol on subjects 1–6; the rest did not complete the test due to time constraints. Subjects 1, 2, 4, and 6 had very good improvement.

has been very positive for the general design and construction. Valuable suggestions are also provided on modification and redesign of RUPERT II.

Limited patient data for ten subjects using RUPERT II is shown in three tables summarized in Fig. 5. The demographics section describes the age, gender, height, and weight of each subject. In this starting phase of design, only moderate and mild subjects were tested.

The modified Wolf Motor Test was given to six participants at the start of the three week therapy protocol and at the end of the protocol. The WMFT is a validated test widely used to quantify motor function in stroke and traumatic brain injury patients [22], [28]. The test consists of 17 items, two of which involve strength measures and 15 of which involve timed performance on various tasks. These assessment motor tasks include simple and complex tasks with increasing demand on multijoint coordination and force levels for increased task complexity. The tasks we used for evaluation include: putting the forearm on to a table, putting the hand to table, forearm reaching to a box, hand reaching to a box, extending the elbow, extending the elbow to push a weight, retrieving a weight, lifting a basket, lifting a can to the lips, picking up a pencil, picking up a paper clip, folding a towel, flip cards, turning a key, and stacking checkers, etc. We only evaluated these 15 tasks. The Fugl–Meyer upper motor assessment test was also utilized [24]. This test is a comprehensive upper extremity assessment test that scores sensation (light touch and proprioception), motor function (reflexes, volitional movement assessment, flexor synergy, extensor synergy, movement combining synergies, movement out of synergy, normal reflex assessment, wrist movement, hand movement and coordination and speed). These tests were performed before and after the three week protocol. More frequent use of these evaluation tools introduces the possibility of test score improvements because of familiarity with the test procedure.

We are encouraged that four subjects improved in both the simple and complex tasks in the Wolf Motor Test by completing each task much faster. Subjects AR-03 and AR-05 could perform and finish all tasks with increasing complexity both at the start of the testing and at the end of the testing. For these two subjects, the difference in measured time was very minimal.

As shown in Fig. 6, the assistive forces by the PM aided patients with various degrees of disability to reach the desired arm extension for reaching movements, though the speed and path were different for different subjects due to their weakness or spasticity. The data shows repetitive joint angles for two participants during a reaching activity. The forearm begins across the body at the waist with elbow flexed and upper arm vertical. During reaching, the shoulder is extended from 45° to 85°. Concurrently, the elbow is extended fully from the initial flexed position. During a regular reaching therapy session, the participant is asked to reach. When the maximum joint positional errors are achieved, RUPERT assists. For the examples shown in Fig. 6, the self actuated and assisted motions are shifted in time so they are superimposed. The first participant had full elbow function and some deficiencies in wrist and shoulder function. The second participant had no shoulder and wrist function and some deficiency in elbow function. These data show the amount of assistance provided during one session for two different participants. Other types of therapy are possible such as holding one of the joints in a fixed position, e.g., shoulder elevation, and then working on one or two of the other joint motions.

VI. Safety

The risk to patients is minimized in this design by utilizing compliant pneumatic actuators, an easy to access shutdown button and using open loop control with limited pressure and the rate of pressure increase. To insure safety, the device physically limits the range of motion of each individual joint. Force application is limited by the compliant nature of the PM actuators. Lastly, emergency switches on the control box and the robot can deactivate the device automatically by exhausting the air from each PM.

Our assertion on the safety is based on the fact that the upper bound limited pressure and range of motion, determined by careful test and evaluation of patient data, will not impose excessive force on a patient if the joint stiffness and/or muscle

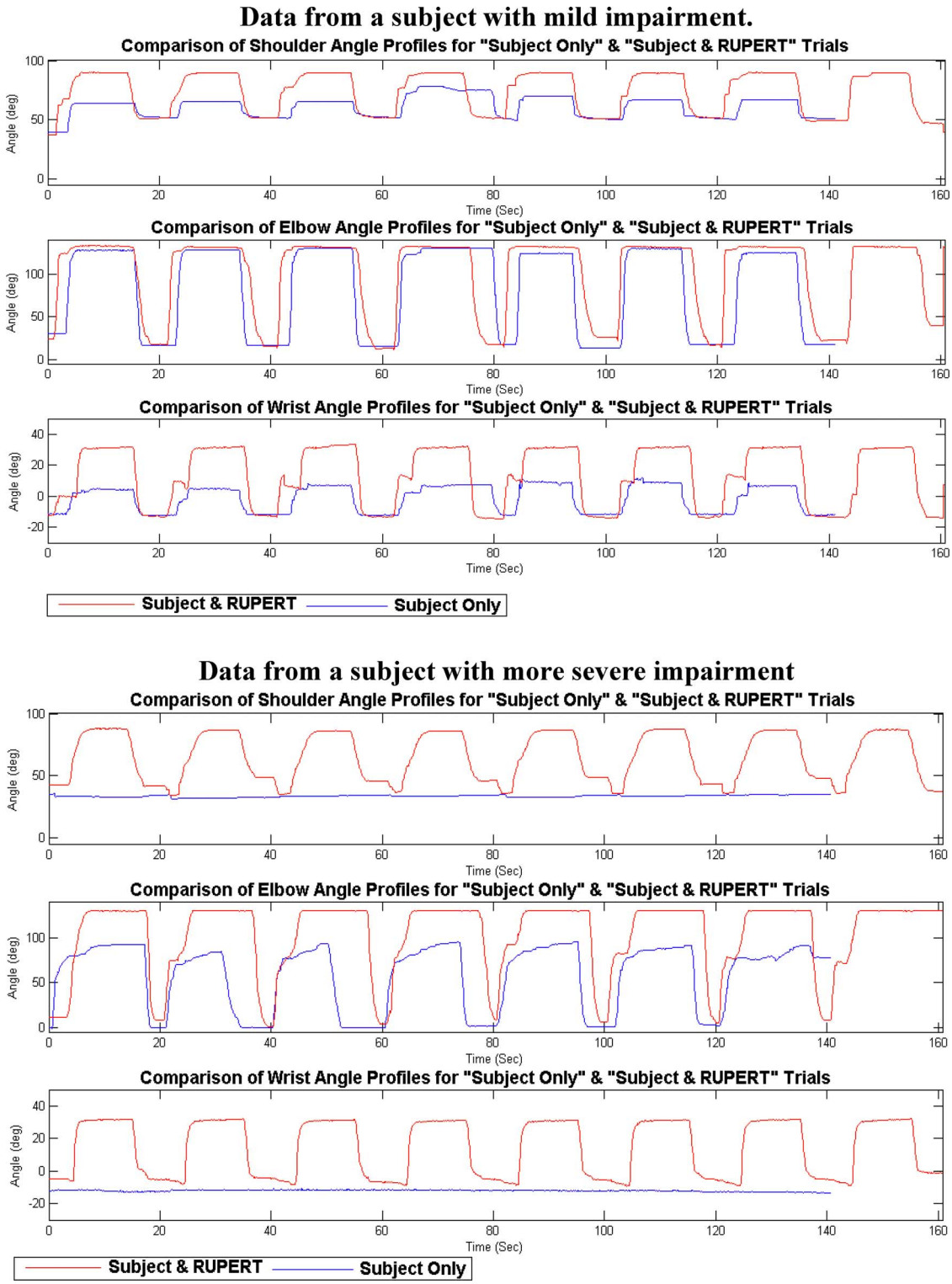

Fig. 6. Shoulder, elbow, and wrist angle for two different subjects is shown over time during a therapy session. Subjects are first asked to attempt a reaching movement without the assistance of RUPERT (subject only). Subjects are subsequently asked to make the same reaching movement and RUPERT assists the subject in the task, permitting much larger shoulder, elbow, and wrist movements. "Subject Only" indicates no robotic assistance is used.

spasm prevent the arm from reaching a predefined target. An emergency shutdown button is in easy reach of the unaffected hand. The shutoff dumps all air from the actuators and stops the program.

A good engineering design of a closed-loop feedback control needs to balance the safety consideration and the desire to achieve more accurate positions in rehabilitation.

VII. Discussion and Conclusion

Stroke is the leading cause of adult disability in the United States and enhanced rehabilitation therapy is needed. Many research studies, both animal and human, have shown that continued recovery of functional skills in stroke survivors occurs with repetitive task therapy. However, health insurers often limit or deny rehabilitation to stroke survivors claiming patients

plateau several months poststroke [21]. Robotic devices that provide treatment capability in the home and clinic offer a way to provide cost effective therapy to a wider population for a longer period of time, which is the purpose of the pneumatic muscle driven RUPERT device. Using a robot assistance device, extra therapy can be achieved reducing the strenuous physical requirements demanded of the therapist.

The device is safe, compliant, easy to use, and very lightweight. It also is able to measure the person's movement and voluntary muscle activity to achieve more systematic therapy at home or in the clinic. For example, the device can provide real-time, objective assessment of functional improvement. Currently, the device assists the user in two critical daily tasks, reaching and feeding, but other tasks can be programmed and implemented. It is very important to note that gravity effect on the arm is not compensated and the daily tasks are practiced in a natural setting. Because the device is wearable, lightweight, and portable, it can be worn standing or sitting in a natural setting providing therapy that better mimics daily tasks.

To limit the stimulation of spastic synergy motions, RUPERT is designed to restrict certain motions and promote "reflex-inhibiting" motions that are incorporated in many everyday tasks. This strategy is recommended by many stroke therapy programs [23].

Many stroke survivors initiate early motion of the scapula in shoulder elevation either because of synergistic interactions or for compensatory reasons. To assist in training the desired motions, the scapula is restricted by the support pad that is part of the attachment structure. The RUPERT IV shoulder design restricts the elevation of the humerus to a plane rotated 30° clockwise from the sagittal plane. This plane is also the most common plane of humeral elevation for activities of daily living [25]–[27]. Eating, reaching, and hair combing typically occur in this plane. This is also the plane of maximal elevation. This plane also approximates the scapular plane. To increase the number of tasks and the reachable space, the next version of RUPERT will include axial rotation of the humerus.

We are continuing our research to improve the functionality of RUPERT. The new features to be developed include additional actuation degrees of freedom for reaching a larger workspace in 3-D, the accommodation of more complex activities of daily living, the further reduction of weight in the device yet providing a more sturdy structure, and more importantly, the development and implementation of an adaptive controller so that the device can interact with users encouraging more voluntary action and active participation during the rehabilitation process, often a key factor related to the positive outcome of the rehabilitation therapy.

APPENDIX
DETERMINING THE PARAMETERS OF A COMBINED MODEL OF RUPERT AND THE HUMAN ARM

The parameters of the link segments of RUPERT were obtained from the solid works model of the device. The length of the upper arm (UA) segment of RUPERT can be varied. Thus, the center of gravity (COG) and the moment of inertia (MOI) for the upper arm are given as functions of the segment length: $L^{\mathrm{UA}}_{\mathrm{Rupert}}$ (Range = 23.151 cm to 34.605 cm).

Mass of the UA of RUPERT (kg)

$$M^{\mathrm{UA}}_{\mathrm{Rupert}} = 0.624\,\mathrm{kg}.$$

COG of the UA of RUPERT (m)

$$\begin{aligned} x^{\mathrm{UA}}_{\mathrm{Rupert}} &= 0.157 L^{\mathrm{UA}}_{\mathrm{Rupert}} - 0.0262 \\ y^{\mathrm{UA}}_{\mathrm{Rupert}} &= -0.889 L^{\mathrm{UA}}_{\mathrm{Rupert}} + 0.0958 \\ z^{\mathrm{UA}}_{\mathrm{Rupert}} &= -0.0132 \\ COG^{\mathrm{UA}}_{\mathrm{Rupert}/O_R} &= \left[x^{\mathrm{UA}}_{\mathrm{Rupert}} \quad y^{\mathrm{UA}}_{\mathrm{Rupert}} \quad z^{\mathrm{UA}}_{\mathrm{Rupert}}\right]. \end{aligned}$$

Inertia Parameters of the UA of RUPERT $(\mathrm{Kg.m}^2)$

$$\begin{aligned} I^{\mathrm{UA}}_{xx} &= 0.0852\left(L^{\mathrm{UA}}_{\mathrm{Rupert}}\right)^2 - 0.281 L^{\mathrm{UA}}_{\mathrm{Rupert}} + 0.00705 \\ I^{\mathrm{UA}}_{yy} &= 0.00260\left(L^{\mathrm{UA}}_{\mathrm{Rupert}}\right)^2 - 0.00566 L^{\mathrm{UA}}_{\mathrm{Rupert}} + 0.000939 \\ I^{\mathrm{UA}}_{zz} &= 0.0878\left(L^{\mathrm{UA}}_{\mathrm{Rupert}}\right)^2 - 0.0286 L^{\mathrm{UA}}_{\mathrm{Rupert}} + 0.00690 \\ I^{\mathrm{UA}}_{xy} &= -0.0149\left(L^{\mathrm{UA}}_{\mathrm{Rupert}}\right)^2 + 0.00408 L^{\mathrm{UA}}_{\mathrm{Rupert}} \\ &\quad - 2.22 \times 10^{-5} \\ I^{\mathrm{UA}}_{yz} &= 2.10 \times 10^{-5}\left(L^{\mathrm{UA}}_{\mathrm{Rupert}}\right)^2 - 0.000144 L^{\mathrm{UA}}_{\mathrm{Rupert}} \\ &\quad + 2.44 \times 10^{-5} \\ I^{\mathrm{UA}}_{zx} &= -0.000119\left(L^{\mathrm{UA}}_{\mathrm{Rupert}}\right)^2 + 0.000815 L^{\mathrm{UA}}_{\mathrm{Rupert}} \\ &\quad + 0.000651. \end{aligned}$$

MOI Matrix for the UA of RUPERT

$$I^{\mathrm{UA}}_{\mathrm{Rupert}} = \begin{bmatrix} I^{\mathrm{UA}}_{xx} & I^{\mathrm{UA}}_{xy} & I^{\mathrm{UA}}_{xz} \\ I^{\mathrm{UA}}_{xy} & I^{\mathrm{UA}}_{yy} & I^{\mathrm{UA}}_{yz} \\ I^{\mathrm{UA}}_{xz} & I^{\mathrm{UA}}_{yz} & I^{\mathrm{UA}}_{zz} \end{bmatrix}.$$

Human Arm Parameters

M	Mass of the subject in kilograms
H	Height of subject in centimeters

Mass of the UA (kg)

$$M^{\mathrm{UA}}_{\mathrm{arm}} = 0.0271 * M(\mathrm{kg}).$$

Length of Upper Arm Segment (m)

$$L_{\mathrm{arm}} = \frac{(-7.99 - 0.239M + 0.279H)}{100}.$$

COG of Upper Arm (m)
(From the proximal end)

$$\mathrm{COG}_{\mathrm{arm}} = [0 \quad -0.450 L_{\mathrm{arm}} \quad 0].$$

Inertia Parameters $(\mathrm{Kg.m}^2)$.

Sagital Axis

$$I^s_{\text{arm}} = \frac{(-251 + 1.56M + 1.52H)}{10000}.$$

Frontal Axis

$$I^f_{\text{arm}} = \frac{(-232 + 1.53M + 1.34H)}{10000}.$$

Proximal Axis

$$I^p_{\text{arm}} = \frac{(-16.9 + 0.662M + 0.0435H)}{10000}.$$

MOI Matrix for the Upper Arm

$$I^{\text{UA}}_{\text{arm}} = \begin{bmatrix} I^s_{\text{arm}} & 0 & 0 \\ 0 & I^p_{\text{arm}} & 0 \\ 0 & 0 & I^f_{\text{arm}} \end{bmatrix}.$$

Combining RUPERT and Human Arm Parameters: Though the coordinate systems of the human arm and RUPERT are parallel, there is an offset between the origins of these two coordinate systems This offset needs to be taken into account when combining the moment of inertias of the two bodies. The calculation procedure is explained below only for the upper arm segment, as the procedure for both the upper and lower arm are the same.

1) Let the offset between the origin of RUPERT ($O^{\text{UA}}_{\text{Rupert}}$) and the origin of the arm ($O^{\text{UA}}_{\text{arm}}$) be $r^{\text{UA}}_{O_A} = [x^{\text{UA}}_{off} \quad y^{\text{UA}}_{off} \quad z^{\text{UA}}_{off}]$. Now, calculate the COG of RUPERT with respect to $O^{\text{UA}}_{\text{arm}}$.

$$\text{COG}^{\text{UA}}_{\text{Rupert}/O_A} = \text{COG}^{\text{UA}}_{\text{Rupert}/O_R} + r^{\text{UA}}_{O_A}$$

where $\text{COG}^{\text{UA}}_{\text{Rupert}/O_A}$ is the COG of the upper arm of RUPERT with respect to $O^{\text{UA}}_{\text{arm}}$. $\text{COG}^{\text{UA}}_{\text{Rupert}/O_R}$ is the COG of the upper arm of RUPERT with respect to $O^{\text{UA}}_{\text{Rupert}}$

2) Find the new COG of the combined arm and RUPERT segments.

$$\text{COG}^{\text{UA}}_{O_A} = \frac{M^{\text{UA}}_{\text{arm}}\text{COG}^{\text{UA}}_{\text{Arm}/O_A} + M^{\text{UA}}_{\text{Rupert}}\text{COG}^{\text{UA}}_{\text{Rupert}/O_A}}{M^{\text{UA}}_{\text{arm}} + M^{\text{UA}}_{\text{Rupert}}}$$

3) Shift the MOI of RUPERT and the ARM to the new COG. Let the distance between the new COG and the COG of RUPERT be

$$d_{\text{Rupert}} = [x_R \quad y_R \quad z_R] = \text{COG}^{\text{UA}}_{O_A} - \text{COG}^{\text{UA}}_{\text{Rupert}/O_A}$$

Thus, the MOI of RUPERT about the new COG is given by,

$$I^{\text{UA}}_{\text{Rupert}/\text{COG}_{\text{New}}} = I^{\text{UA}}_{\text{Rupert}} + M^{\text{UA}}_{\text{Rupert}} \begin{bmatrix} y_R^2 + z_R^2 & -x_R y_R & -x_R z_R \\ -x_R y_R & x_R^2 + z_R^2 & -y_R z_R \\ -x_R z_R & -y_R z_R & x_R^2 + y_R^2 \end{bmatrix}$$

Similarly, let the distance between the new COG and the COG of the human arm be

$$d_{\text{arm}} = [x_A \quad y_A \quad z_A] = \text{COG}^{\text{UA}}_{O_A} - \text{COG}^{\text{UA}}_{\text{Arm}/O_A}.$$

Thus, the MOI of the human arm about the new COG is given by

$$I^{\text{UA}}_{\text{Arm}/\text{COG}_{\text{New}}} = I^{\text{UA}}_{\text{arm}} + M^{\text{UA}}_{\text{arm}} \begin{bmatrix} y_A^2 + z_A^2 & -x_A y_A & -x_A z_A \\ -x_A y_A & x_A^2 + z_A^2 & -y_A z_A \\ -x_A z_A & -y_A z_A & x_A^2 + y_A^2 \end{bmatrix}$$

4) Add the two MOIs to obtain the final total MOI.

$$I^{\text{UA}}_{\text{Rupert+Arm}} = I^{\text{UA}}_{\text{Rupert}/\text{COG}_{\text{New}}} + I^{\text{UA}}_{\text{Arm}/\text{COG}_{\text{New}}}$$

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