Tabletop Robot to Aid in Arm Rehabilitation of Stroke Patients

by

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ABSTRACT

The aim of this project was to design and build a tabletop robot that could move the arm of a patient with limited motor function around on a table in any given trajectory to aid the patient in regaining function. The design that resulted from bench level experiments was that of an arm brace mounted to a moving base. The base needed to be omni directional to accommodate all possible trajectories of motion, the arm brace needed to be able to move vertically as well as be flexible enough to accommodate yaw, pitch and roll of the forearm.

After choosing a three-wheeled design using TransWheels^{TM}, the base of the robot was built and programmed by Adam Kraft. The arm brace, which I designed and built, had a rack and pinion setup with a variable voltage regulator to control its vertical motion and a foam and linear spring combination to allow for yaw, pitch and roll while still providing for support.

Testing of the prototype proved extremely valuable in refining the requirements of the robot as well as the design. Issues that were discovered during testing of the robot included drift of the robot, the inability to orient the robot the same each time, the slipping of the pinion on the rack if too much downward force is applied to the arm brace and the stiffness of the arm brace during yaw, pitch and roll. Several suggestions were made for possible solutions to the issues, all which seem very feasible to implement.

As it is the robot can only move the patient's arm, the patient cannot move the robot since the motors are not back-drivable. This is an impediment in allowing the patient to initiate movement, which is a critical part of therapy. Solutions were proposed that are worth further examination to determine their feasibility. In addition, with a few changes, the robot act as a guide to move a patient's passive arm along a preprogrammed trajectory to aid the patient in performing tasks such as reaching. Even if the robot is unable to match its initial goal, it has great potential to become a valuable asset to stroke patients with limited arm motor function.

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1.0 Introduction

Over 600,000 people in the U.S. suffer a stroke each year. Out of the survivors, approximately 80% lose motor function in their arms and hands.[1] In order to regain these skills, intensive physical and occupational therapy over long periods of time is needed. A common form of therapy is a "hand-over-hand" method where a therapist put his hand over the patient's to guide the patient's movement until the patient regains control.[2] With recent economic pressures in the healthcare system however, stroke survivors are being discharged earlier and receiving less therapy, causing their progress to be halted at a level below its potential.[3]

Previous studies have shown that the greatest recovery of motor function after a stroke is within the first month of onset, with some more improvement up to 6 months poststroke.[4] Recent studies have shown however, that intensive therapy can produce significant improvements in motor function years poststroke.[5] These new studies are suggesting that the plateau stroke patients reach after 6 months may be a false one brought on by lack of rehabilitation and therapy. If patients were able to continue therapeutic rehabilitation, they may have the chance of regaining more motor function.

To address this issue, several mechanized rehabilitators have been developed to supplement the role of the therapist. These rehabilitators work by having mechanical components support and guide the hand and arm of the patient. The machines however, are limited for distribution due to both cost and size constraints.

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[1] Reinkensmeyer, David J., Clifton T. Pan, Jeff A. Nessler, Chris C. Painter. *Java Therapy: Web-Based Robotic Rehabilitation.* http://www.eng.uci.edu/~dreinken/publications/us05.pdf.

[2] Hogan, N.; Krebs, H.I.; Charnnarong, J.; Srikrishna, P.; Sharon, A.; *MIT-MANUS: a workstation for manual therapy and training. I* Robot and Human Communication, 1992. Proceedings., IEEE International Workshop on , 1-3 Sept. 1992. Pages:161 - 165

[3] Reinkensmeyer DJ, Lum PS, Winters JM. *Emerging Technologies for Improving Access to Movement Therapy following Neurologic Injury*. In: Winters JM (editor), Emerging and Accessible Telecommunications, Information and Healthcare Technologies - Engineering Challenges in Enabling Universal Access. IEEE Press 2002. http://www.eng.uci.edu/~dreinken/publications/djr%20resna%20chapter.pdf

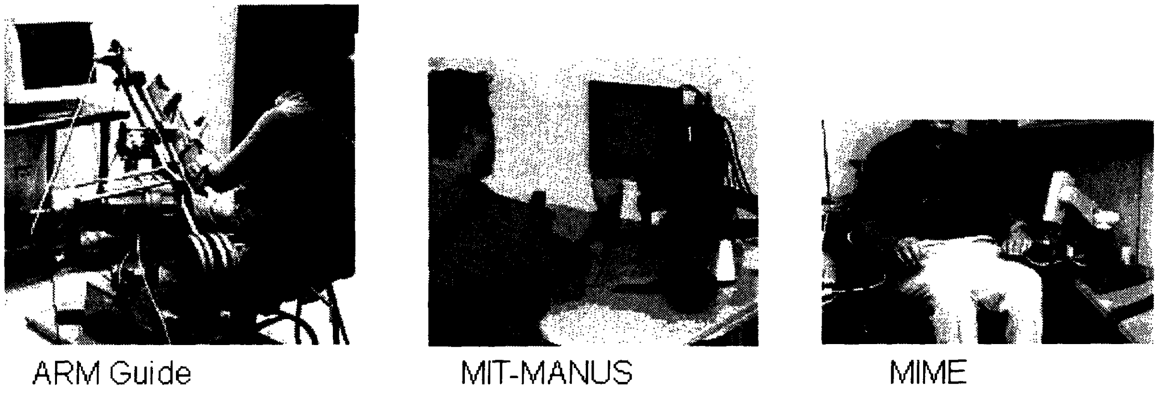
[4] Duncan, PW, LB Goldstein, D Matchar. *Measurement of motor recovery after stroke.* Stroke 1992;2:1084-9.

[5] Fasoli, Susan E. Hermano I Krebs. *Robotic Therapy for Chronic Motor Impairments After Stroke: Follow up Results*. Arch Phys Med Rehabil. July 2004:Vol 85:1106-11.

1.1 Current Robotic Therapies

Three existing robotic devices for arm rehabilitation include the MIT-MANUS developed by Profs. Neville Hogan and Hermano Igo Krebs at the Massachusetts Institute of Technology, the MIME system developed at the Veterans Affairs Palo Alto Rehabilitation Center, and the ARM guide at the Rehabilitation Institute of Chicago. These devices are shown in use in Fig. 1. As can be seen, all three devices are large in size, complicated in construction and require a great deal of hardware for use. They are also stationary and fixed to one place.

These robotic devices have three modes of function. In passive mode, the patient relaxes as the robot moves their arm towards a specific target via a predetermined trajectory. In active-assist mode, the patient initiates movement towards a target or follows a trajectory and the robot aids the patient in staying on track. In active-resist mode, the robot provides a resistance to the motion as the patient tries to reach the desired target. In some cases, the patient interacts with a computer in a video game program to move and reach targets. In other cases the patient is focused on completing a specific task such as reaching an object. Both cases provide a way of engaging the patient in the therapy.



ARM Guide MIT-MANUS MIME

Figure 1. Pictures of the ARM Guide, MIT-MANUS and MIME in use by patients.

The ARM guide is a singly actuated, three degree of freedom (DOF) device to assist in reaching movements. Linear bearings are used to guide movements by the patient and can be oriented at different yaw and pitch angles to accommodate different workspaces. The ARM guide can either assist or resist the patient's movements and measures hand movement and force generation. The MIT-MANUS assists in shoulder and elbow movement by moving the hand and forearm of a patient. With a unique feature that allows for back-drivability of motors, the device can measure free movements and guide the arm in "hand-over-hand" therapy. Patients using MIT-MANUS showed statistically improved results at the 1 year and 3 year follow ups.[6] The MIME system applies forces to the arm through a customized forearm and hand splint. It too can assist, resist or move the patient's arm.

Studies have shown that the improvements of patients using robotic therapy are not statistically greater than those of patients undergoing traditional therapy. The problem is however, that patients do not always have access to a traditional therapy poststroke due to financial or other reasons. A robotic device will be able to provide patients with the access to some form of therapy, and thereby increasing their chances of regaining motors function especially if it can be made for in home use. As mentioned above however, existing devices are too large and costly to be widely distributed for at home use.

2 Statement of Problem

The goal of this project is to design a smaller and less expensive version of a mechanized rehabilitator for use at home. The device would be an autonomous tabletop robot that will move the patient's arm around on the table in any direction, mimicking the passive mode of existing devices. The design of the robot should also allow for active-assist and active-resist functions to be implemented in the future. The robot can be programmed to move the patient's arm around in certain trajectories and perform tasks such as reaching movements.

3.0 Defining the Robot's Requirements

In order to determine what the functional requirements of the robot were, the first thing was to simulate the motion of reaching for something on the table as well as other

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[6] Volpe, B, H Krebs, N Hogan. *Robot training enhanced motor outcome in patients with stroke maintained over 3 years*. Neurology, vol 53, pp 1874-6, 1999.

tabletop motions to see what the motion entailed. A bench level experiment was performed with a mockup as seen in Fig. 2. The mockup consisted of a platform mounted on three caster wheels with a support on it for the subject's arm. The subject placed one arm in the support and moved the base around with their other arm.

Figure 2. Bench level experiment to determine required motions.

It was found that the robot needed to be able to move the arm in any direction on the plane of the table. The arm also needed to be able to move up and down in the vertical direction. As the arm was being moved around, it was discovered that the arm yawed, pitched and rolled with the elbow as the point of pivot.

3.1 Product Specifications

After the bench level experiments were performed, the information gathered was used along with research of existing devices, to draw up a product specification chart for the robot. The chart, shown in Table 1, lists the needs of the customers with respect to the robot and translates those needs into quantitative engineering specifications.

Table 1. Product Specification Chart for Robot

Customer Need	Design Attribute	Engineering Specification
Robot can repeat any preprogrammed motion	Direction of motion in plane of table	The robot can sweep out any trajectory on the table- linear, circular, and rotational motion
Patient's arm can yaw, pitch and roll	Allowable rotation of arm	The arm needs to have the freedom to rotate 45° in any of the three directions
Arm needs to reach different heights	Vertical motion of arm	The arm needs to have a vertical motion of 0.3m.
Fit of arm in robot	Adjustability	Brace should be able to fit one standard deviation above and below the arm size of an average stroke patient
Safety	Ability to stop and release patient	Motors should be able to stop at the press of the button and user can take out arm Robot will not move faster than 0.5m/s and not accelerate faster than 0.5 m/s^2.
Battery needs to last a long time	Battery life, number of uses per charge	Battery can last two half hour sessions before recharging. Battery should last two years before needing replacement.

3.2 Functional Requirements

From the engineering specifications in the product specification chart, the functional requirements of the robot were determined. The requirements were put into the FRDPARRC chart in Appendix A. For simplicity sake, the scope of this project focused on meeting three requirements in the prototype: the motion of the robot on the table, the vertical motion of the arm brace and the rotational motion of the arm. The battery choice was also examined but not implemented in this project.

4.0 Selection of Strategies

From the determined functional requirements, the best design for the robot appeared to be an arm brace with the ability to yaw, pitch and roll as well as move vertically up and down attached to a base that could move in any direction on the table. Several strategies were examined to see which one would perform the functional requirement the best with the least amount of risk. In some cases however, the analysis was not implemented completely in the prototype due to material constraints. Fig. 4 shows the completed first generation prototype which consists of an arm brace built by me on top of a rolling base built by Adam Kraft.

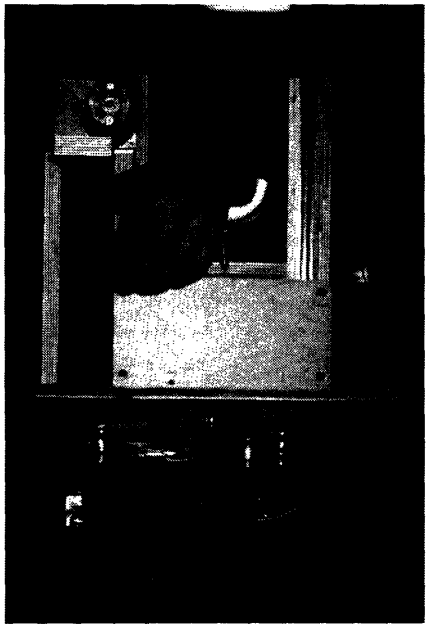

Figure 3. Picture of prototype with arm brace on top of the base.

4.1 Wheel Orientation on Base

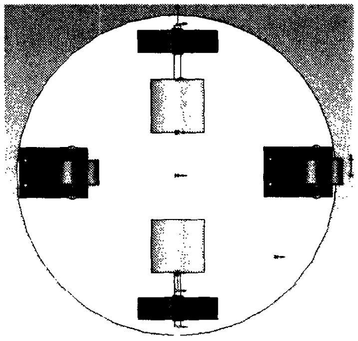

Figure 4. Bidiectional wheel design with two driven wheels on the top and bottom and two caster wheels on the left and right

The requirement for the base was that it be able to move in any direction on the table. The caveat was that since the arm brace is attached to it, its motion could not hurt the arm in any way. The first design looked at for the position of the wheels was a simple two wheel drive on two opposite sides with two casters wheels on the other two sides seen in Fig. 4. This orientation however, is bidirectional in the axis of the two driven wheels. This means that the two driven wheels must be parallel to the direction of motion. For example, in order to move a patient's arm forward and then to the right, the robot would have to move forward, rotate 90° and then move to the right. If the brace was fixed to the robot, it would of course not be a natural motion for the arm. Therefore in order for the arm to move with the robot, it would have to rest on a thrust bearing on top of the base. Not only would this add parts to the robot, making it more complicated, it would also reduce the amount of control the robot had on the orientation of the arm. Therefore this wheel orientation did not fit the requirements very well.

The second wheel orientation analyzed was a three-wheeled design using wheels that were free rotating in one direction and power rotated in the orthogonal direction, shown in Fig. 5. This orientation has been used before in creating omnidirectional robots for the international RoboCup competitions.[7] Omnidirectional locomotion is the ability to move in any direction while facing any orientation. This means that the robot can move forward and then to the right without changing orientations. The arm brace would also stay in the same orientation. The possible designs are compared in Table 2, with the three-wheel design fulfilling the functional requirements the best.

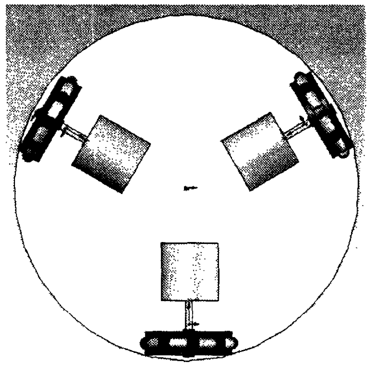

Figure 5. Omnidirectional wheel design with three wheels 120° apart.

Table 2. Comparison between wheel designs.

Requirement	Two-wheel Drive	Three-wheel Drive
Can follow any trajectory on table	Yes	Yes
Will not move arm in an unnatural motion when following trajectory	Only when a thrust bearing is used to support arm brace	Yes
Can control orientation of arm along with the x,y position	Only if motion on thrust bearing is actuated	Yes
Ease of implementation	Easy is thrust bearing is free rolling, hard if thrust bearing is actuated	Hard but there are previous examples of similar designs

The wheels needed for the three-wheel design are commercially available from The Kornylak Corporation and are shown in Fig. 6. Each wheel, called a TransWheel™ consists of 8 free-rotating rollers that roll in the direction perpendicular to the axel of the

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[7] Brian Carter, Matt Good, Mike Dorohoff, Jae Lew, Robert L. Williams, Paolo Gallina, "Mechanical Design and Modeling of an Omni-directional RoboCup Player," *RoboCup AI Conference,* Seattle WA, August 2001, p. 1—10.

wheel. Each wheel would be driven by its own motor that acts independently from the other motors. To sweep out a path, the trajectory of the path would have to be broken up into the individual components for each wheel that is dependent on the current orientation of the robot.

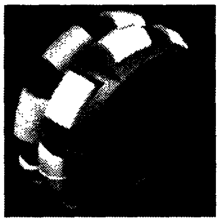

Figure 6. Omnidirectional wheel from Kornylak Corp. http://www.kornylak.com/wheels/transwheel.html.

With the three wheeled design where each motor is acting independently of the others, it is possible that only one motor is being used to drive the robot while the other wheels are sliding. Therefore, when analyzing the characteristics of the motor for the wheels, it was thought best to size it so that one motor can drive the entire robot. Because the arm is passive when it is being moved, the mass of the arm is the only thing the robot has to move as long it travels within the arm's range of motion. When the patient's arm has been moved out of its range of motion and the patient must move their upper body to keep up with the robot, there is a resistance force on the robot. Since the interest here is on increasing the motor function on the arm, the movements initiated by the robot will be limited to only within the arm's range of motion.

The maximum linear velocity of the robot is assumed to be v=0.5 m/s for safety reasons and the entire mass of robot plus the patient's arm is m=10 kg based on the average of five arm masses. The coefficient of friction between the wheels, assumed to be rubber, and the table is μ=.75. Finally, the radius of the wheels is assumed to be r=.0508 m based on the sizes available from Kornylak.

The torque needed to overcome the frictional force of the robot at a constant velocity is found by

$$\Gamma = (mg)\mu \cdot r$$

where g is the gravitational acceleration of 9.8 m/s^2. The torque therefore is Γ=3.75 Nm. If a maximum acceleration of a=0.5 m/s^2 is assumed for the robot, the torque of the motor now becomes:

$$\Gamma = [(mg)\mu + ma] \cdot r$$

and the torque needed during acceleration is Γ=3.99 Nm.

With the assumed linear velocity, the angular velocity of the robot is w=9.8 rad/s and the revolutions per minute is rpm=94. For maximum efficiency when running the motor, the torque and speed should be half of that stall torque and no load speed respectively. Therefore the ideal motor would have a stall torque of 8 Nm and a no load speed of 200 rpm. The load power requirement of the motor can be calculated by $P= \Gamma w$ which comes to P=36.75 W. The MATLAB script for the calculations involved is in Appendix B.

After I had chosen the wheel design and performed the calculations for the motors, a prototype of the base was built and programmed by Adam Kraft. For the actual prototype, 2 inch TransWheels™ were ordered from Kornylak as seen in Fig. 7. The block diagram of the details of the programming, supplied by Adam Kraft, is in Appendix C.

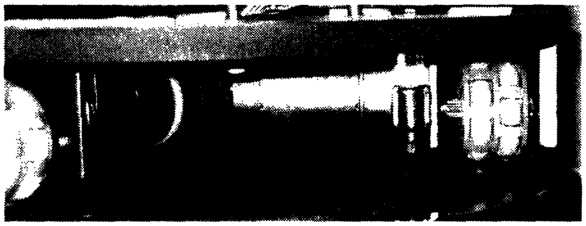

Figure 7. Motor and TransWheels™ on robot prototype.

4.2 Vertical Motion of Arm

The functional requirements for vertical motion of the arm are the ability move a distance of 0.3m upward, a maximum speed of 0.5 m/s and a tolerance of 0.005 m. The vertical motion of the arm brace, a mechanism was needed to transform the rotary motion of a motor into linear motion. There are several ways that linear motion can be achieved, including leadscrews and racks.

Leadscrews work by sliding a nut's thread along the thread of a screwshaft. Either the nut is held so that it can only translate and cannot rotate or a screwshaft that's prevented from translating is rotated. Leadscrews can be very accurate in its linear motion because multiple thread turns can be simultaneously engaged to average out errors. They are also very easy to manufacture, use and maintain. Although leadscrews can have lead error when the axial distance per rotation of the screwshaft is not constant due to errors in the thread profile, the error is much less than the precision needed in this vertical motion.

With a nut and screw both made be of steel, the coefficient of friction between them is $\mu=0.2$.[8] The thread root stress concentration is assumed to be on the order of 2.[9] The maximum force needed to be generated by the leadscrew, which is required when raising the arm brace, is the mass times the combined acceleration of gravity and that of the moving brace, $F=m(g+a)$ where a is 0.5 m/s^2, which gives F=103 N.

The efficiency of this design when raising the arm brace and the subsequent torque required for the screw is

$$\eta_{raise} = \frac{(\cos\alpha - {}^{\mu\beta}/_{\pi})}{(\cos\alpha + {}^{\mu\pi}/_{\beta})}, \beta = {}^{l}/{d_{pitch}}$$

$$\Gamma_{raise} = \frac{F \cdot l}{2\pi \cdot \eta_{raise}}.$$

The efficiency of the thrust bearing and the torque required is

$$\eta_{bearing} = \frac{l}{l + d_{bearing} \cdot \mu \cdot \pi \cdot \eta_{raise}}$$

$$\Gamma_{bearing} = F \cdot {}^{d_{bearing}}/_{2} \cdot \mu.$$

The total torque of the system is $\Gamma_{total}=\Gamma_{raise}+\Gamma_{bearing}$ and the total efficiency is $\eta_{total}=\eta_{raise}\bullet\eta_{bearing}$. With the desired linear velocity of v=0.5 m/s, the revolutions per minute required of the motor is rpm=$(60v)/l$ and the angular velocity is $\omega = {}^{rpm \cdot 2\pi}/_{60}$.

The critical force the screwshaft can withstand before buckling is dependent on the constraints at the ends of the shaft; in this design the shaft is fixed both translationally and rotationally at both ends. The force is given by

$$F_{cr} = \frac{cEI}{L^2}$$

where I is the moment of inertia for the shaft, c is the coefficient based on the end conditions of the beam and L is the length of the beam. For a circular beam $I = \frac{\pi d^4}{64}$, the c coefficient for a beam that is fixed for both translation and rotation at the ends is 39.5.

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[8] http://www.roymech.co.uk/Useful_Tables/Tribology/co_of_frict.htm

[9] http://pergatory.mit.edu/2.007/lectures/final/Topic_06_Screws_and_Gears.pdf

The length of travel for the beam is L=0.3m, and the Young's Modulus for steel is E= 200 GPa.

Table 3 shows the results of the analysis using the above equations. It is a modified version of the spreadsheet *leadscrew_design.xls* from the 2.007 website.[10] From the results of the analysis, a good design for the leadscrew is a lead of 5mm and a pitch diameter of 7.5mm. The optimal motor would have a stall torque of 0.5 Nm, a no load speed of about 12000 rpm and a power requirement of 178 W. The critical force to buckling for the shaft is also much greater than the applied force of the arm so there is no risk in buckling of the shaft.

Table 3. Results of analysis of leadscrew design.

Leadscrew Design	
Force to raise brace (F), N	103
Lead (l) mm	5
Coefficient of friction (μ)	0.2
Screw pitch diameter (d*screw*), mm	7.5
Thrust bearing diameter (d*bearing*), mm	10
Thread angle (α), degrees	30
Thread root stress concentration	2
β	0.66
Thread efficiency to generate force, η*raise*	46%
Thrust bearing efficiency, η*bearing*	64%
Total system efficiency, η*total*	29%
Torque required at screw (Γ*raise*), N-mm	180
Torque required at thrust bearing(Γ*bearing*), N-mm	103
Total torque, Γ*total,* N-mm	283
Backdriveable?	NO
Linear Velocity (mm/s)	500
Motor speed, w (rpm, rad/s)	6000
Motor speed, rad/s	628
Motor torque, gammotor (N-mm)	283
Power, Preq (watts)	178
Critical Force to Buckling	
Travel length, mm	300
Root Diameter, mm	7.5

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[10] 2.007 Speadsheets. http://pergatory.mit.edu/2.007/software_tools/spreadsheets.html.

Outer Diameter, mm	0.008
Young's Modulus (E), M/m^2	2.00E+11
Inertia I (m^4)	1.5E-10
c coefficient	39.5
Force Critical, N	13633

To find the minimum thread engagement length needed to prevent shearing of the threads in the nut, we can assume that the threads shear mid-plane and start shearing when the shaft starts breaking.[11] From these assumptions, we can set the tensile force of the bolt at breaking to the shear force of the nut

$$F_{nut\_shear} = F_{bolt\_tensile}$$

$$\frac{l_{nut}}{2} \cdot d_{pitch} \cdot \frac{\sigma_{yield}}{2} \cdot \pi = \frac{\pi \cdot d_{root}^{2} \cdot \sigma_{yield}}{4}$$

Assuming that the nut and bolt are made of the same material thus having the same yield strength and that $d_{pitch}=d_{root}$, the minimum length of thread engagement $l_{nut}=d_{pitch}$.

A rack is a linear gear that is driven by a pinion attached to the shaft of a motor. Although the rack and pinion setup does not provide a mechanical advantage like the leadscrew, it is very easy to implement. Assuming the same mass as above, m=10kg, and a pinion radius of r=0.0127m, the torque needed drive the patient's arm up when ignoring friction is given by

$$\Gamma = mg \cdot r$$

which comes to Γ=1 Nm. Again the maximum linear velocity of the brace is v=0.5 m/s, so that the angular velocity of the pinion is w=39 rad/s and the rotations per minute is rpm=375. Therefore the optimal motor would have characteristics of a stall torque of 2 Nm and a no load speed of 750 rpm. The load power requirement is P=39 W. The MATLAB script for these calculations is shown in Appendix D.

One thing to be careful with regarding a rack and pinion is that if the axial force is too large, the pinion's teeth may break off in the long term. An analysis on the gear teeth strength of the pinion was done using the *Rack_and_pinion_design.xls* spreadsheet from the 2.007 website, shown in Table 3. It is usually desirable for the gear teeth strength to

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[11] http://pergatory.mit.edu/2.007/lectures/final/Topic_06_Screws_and_Gears.pdf

be twice the load for a safety factor of 2. The equations for the analysis are shown in Appendix E.

Table 4. An analysis of the gear teeth strength of the pinion.

Inputs	
Pitch, P	24
Pressure angle, alpha (degrees)	14.5
Number of teeth on pinion, N	24
Tooth material	Nylon
Allowable bending stress, (psi)	6000
Tooth width, (in)	0.250
Tooth Geometry	
Circular pitch (in)	0.13
Tooth height (root to tip), (in)	0.104
Addendum, (in)	0.042
Dedendum, (in)	0.052
Clearance, (in)	0.010
Tooth thickness, (in)	0.065
Tooth thickness at root, (in)	0.097
Shear area, (in^2)	0.016
I/C at root, (in^3)	3.9E-04
Distance pitch line to root, (in)	0.062
Gear Teeth Strength	
Maximum tangential force to shear failure, (lbs)	49.1
Maximum tangential force to bending failure, (lbs)	37.5
Maximum allowable tangential (rack) force, (lbs)	37.5
Resulting force along line-of-action, (lbs)	38.7
Resulting spreading force, (lbs)	9.7

Given the characteristics of the pinion, the maximum tangential force that can be applied before the teeth break is F_{max}=37.5lbs which is 166N. Although the maximum force is not quite twice the load, it is still more than 1.5 times the load which will be sufficient for the purposes of a first generation prototype.

Even though the motion of the rack is linear, there is separation force normal to the direction of motion that pushes the pinion away from the rack. This separation force is calculated by

$$F_{separation} = \frac{\Gamma \cdot \sin \alpha}{r}$$

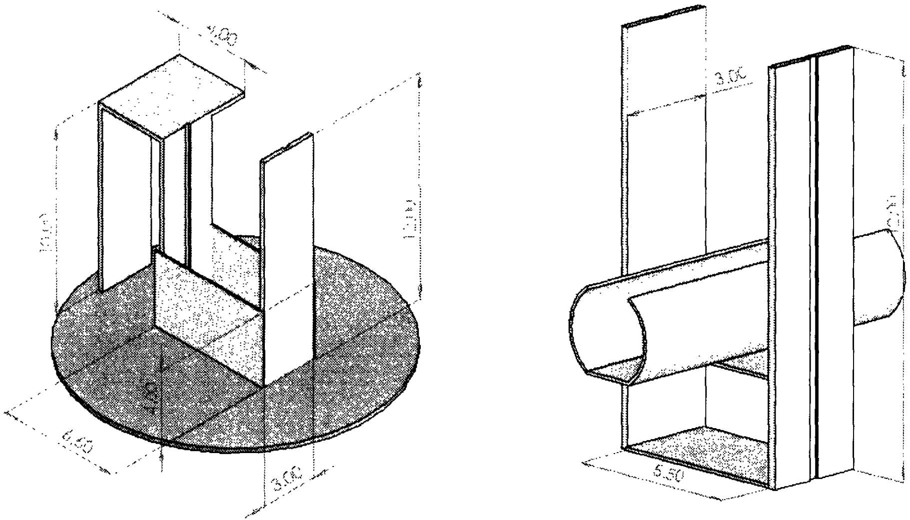
where α is the pressure angle of the pinion gear. In this case, the separation force pushing the pinion away is $F_{separation}$=19.7N.

A table of the possible implementations for vertical motion of the brace is summarized in Table 5. The rack and pinion design was chosen based on ease of implementation and available materials.

Table 5. A comparison of designs for vertical motion

Requirements	Leadscrew	Rack and Pinion
Accuracy within tolerance of system	Yes	Yes
Motor Characteristics	Stall torque: 0.5 Nm No load speed: 12000 rpm Power: 178W	Stall torque: 2 Nm No load speed: 750 rpm Power: 39W
Easy to Implement	Yes	Yes-easier than leadscrew
Risks	None	Separation force btw rack and pinion

To implement the rack and pinion on the prototype, two frames were built with the motor and pinion on the stationary frame and the rack attached to a sliding frame. The outer stationary frame was attached to the base of the robot as shown in the dimensioned drawing in Fig 8. The frame has two panels on the sides to keep the taller pieces upright and to prevent them from bending or tilting. The arm brace was attached to an inner frame in a dimensioned drawing in Fig 8. The inner frame is meant to be able to slide up and down inside the outer frame. On one side between the inner and outer frames will be a guide that serves the purpose of reducing friction between the two frames as well as supporting the inner frame so that it does not tilt from side to side or back and forth. The guide chosen in this prototype was a full extension drawer slide with ball bearings, as shown in Fig 9.



Outer Frame

Inner Frame

Figure 8. Dimensioned diagram of the outer and inner frames.

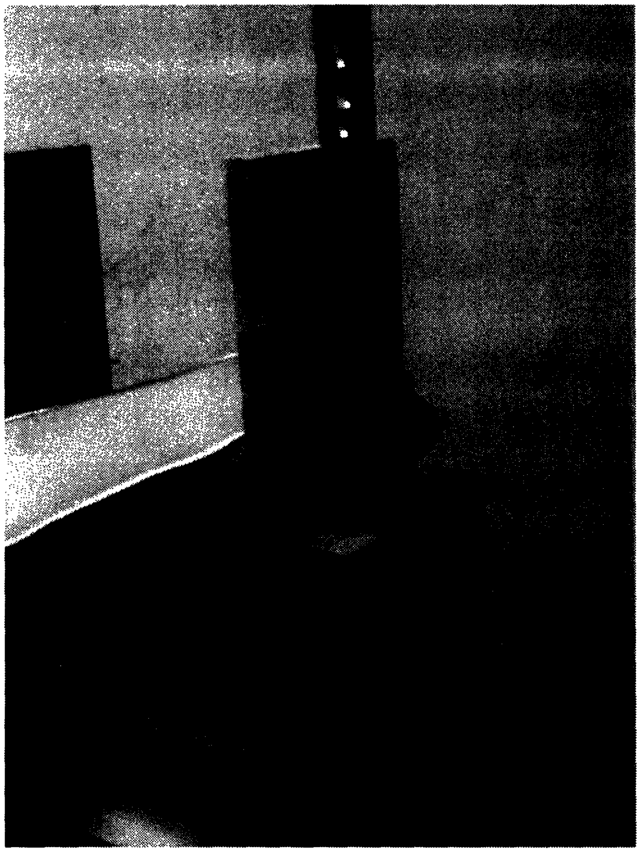


Figure 9. A picture of the drawer slide. One side is attached to the outer frame and one to the inner frame.

One segment of the slide was attached to the other frame and the other segment was attached to the inner frame. On the other side of the inner frame, the rack was attached.

The shorter side of the frame has a platform for which to mount the motor and pinion. A detailed sketch of this setup is shown in Fig 10. The pinion was attached to its shaft using a set-screw. The shaft is supported on both sides by bearing blocks. One end of the shaft is attached to the motor shaft through a coupling made of brass. The coupling prevents the motor shaft from being over-constrained due to any misalignment between the motor and pinion shafts. A final assembly of all the components is shown in Fig. 10.

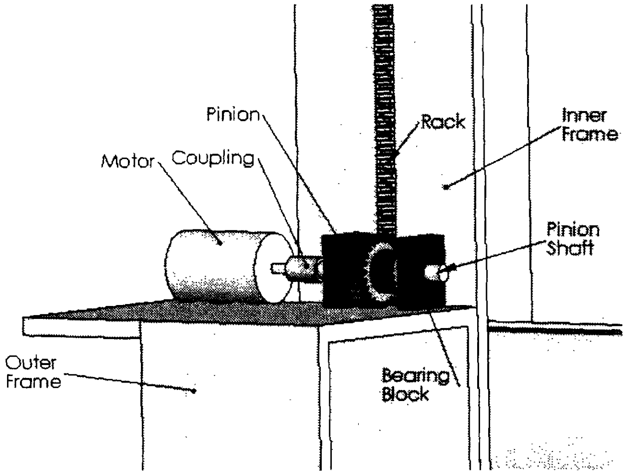


Figure 10. A labeled diagram of the rack and pinion setup

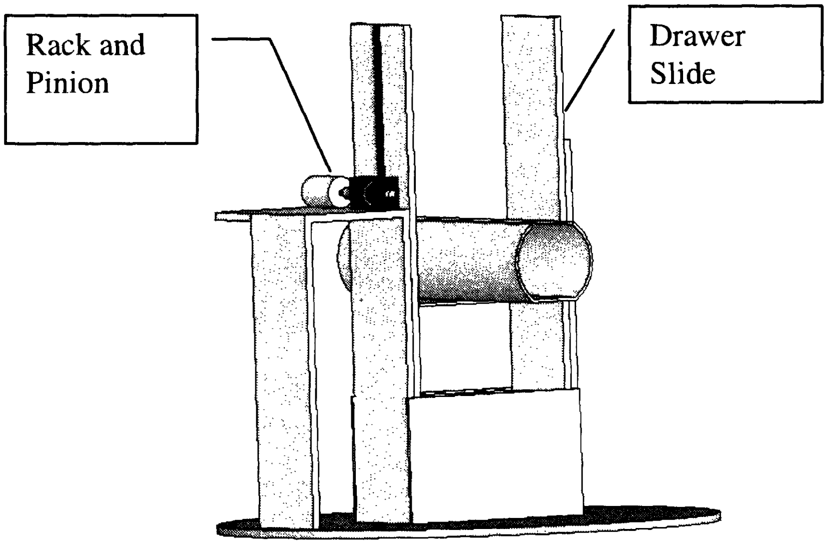


Figure 11. The final assembly of the outer and inner frames.

For the prototype, the motion of the arm brace was controlled by a variable voltage regulator circuit shown in Fig. 11 that allows the AC input from a wall plug to be converted into usable DC current for the motor. The 120V AC input is stepped down using a variable transformer to a different voltage. Next the voltage is rectified using a bridge rectifier to get rid of the negative swings and filtered to obtain a nearly flat DC signal which is used to drive the motor (M). The motor is connected to a switch that can reverse the polarity of the power input from position a to position b. Reversing the polarity will cause the motor to rotate in a different direction, thus being able to move the inner frame up and down.

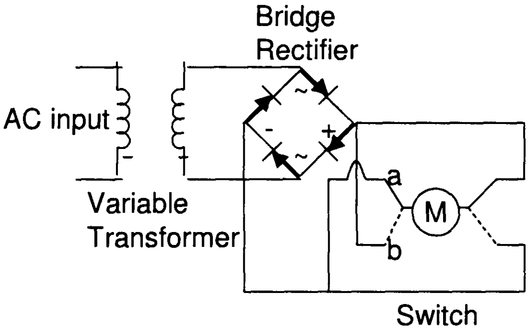


Figure 12. Voltage regulator circuit for controlling motor for pinion

4.3 Rotation of Arm

As the arm brace is raised and lowered, the forearm will yaw, pitch and roll. To accommodate this motion, the arm brace needs to have a fair amount of flexibility in its attachment to the inner frame. However the brace also needs to be supported enough so that the rotating motions are smooth and slow rather than sudden and jolting. One method is to mount the brace on a trackball-like device. That way the brace would be free to rotate in all directions. With a trackball however, there is no resistance as the arm is rotating and therefore no support for the arm. The trackball mechanism would also be hard to implement in the prototype.

Another method of adding flexibility to the arm brace is to rest the brace on some foam. The foam would cushion any rotation of the arm and can always support the brace. The foam alone however, did not provide enough resistance for arm movement. Therefore two linear springs were connected between the brace and the inner frame on either side of the frame to provide resistance as shown in Fig. 12.

Figure 13. Foam and linear springs to give flexibility to the arm brace.

4.4 Battery

In order for the robot to be autonomous, it should be equipped with a secondary battery source. The two top choices for a rechargeable battery would be Nickel Cadmium (NiCad) or Lithium Ion (Li-ion). Table 6 gives a comparison between important characteristics of the two types.[12]

Table 6. Comparison chart between NiCad and Li-ion rechargeable batteries.

Characteristic	NiCad	Li-ion
Energy Density (Wh/kg)	40-60	100
Average cycle life[1]	700	1000
Self-discharge per month[2]	20%	10%
Typical Battery Costs	$50.00	$100
Cost per cycle[3]	$0.04	$.10-.20
Maintenance	High- must be periodically charged and discharged to prevent memory effect	Low- no periodic discharge needed, no memory

[1] *Life cycle based on battery receiving regular maintenance.*

[2] *Discharge at room temperature.*

[3] *Derived from price of battery divided by cycle life, does not include charger and electricity costs.*

As can be seen from the table, the performance of Li-ion batteries are better in energy density, average cycle life and self-discharge rate than NiCad batteries. In addition, NiCad batteries have the risk of memory effect; memory effect occurs when the battery is being continually discharged to a certain level so that after a while it will not longer function below that level. Li-ion batteries however, are twice as expensive as NiCad ones. Both types of batteries are well suited for the needs of the robot; discerning which

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[12] Cadex Electronics. *Choice of Batteries.* http://www.allegromicro.com/techpub2/cadex/index3.htm.

one to use may come down to specifics in the robot design and consumer preference for low costs versus high performance.

If a typical therapy session with the robot last half an hour, the energy consumption of the robot for one session would 40 Wh. In order to last through two sessions without needing to be recharged, the battery would have to have an energy capacity of at least 80 Wh. If the patient has a therapy session 4 times a week, it comes to 416 times in 2 years. With recharging every two sessions, the battery will experience approximately 200 charges within the two years. This is well within the limits of the cycle life for both types of batteries.

For the prototype, three lead acid batteries were used to power the three motors for the wheels. The lead acid batteries were used because of their availability and the extra weight they supplied to the robot in place of a patient's arm.

5.0 Testing

Each implemented strategy above was tested for how well it met the functional requirements. Any errors or problems were identified during testing and possible solutions are suggested.

5.1 Omni-directionality

The base was tested in a variety of different trajectories including straight paths, curved paths, in place rotation and combinations of the three. Fig. 13 shows some of the sample trajectories that the base swept out. The base was indeed omni-direction, it could move in any direction in any orientation. The robot was tested at different speeds and the range of speeds found for comfortable arm motion was 0.1m/s - 0.5 m/s.

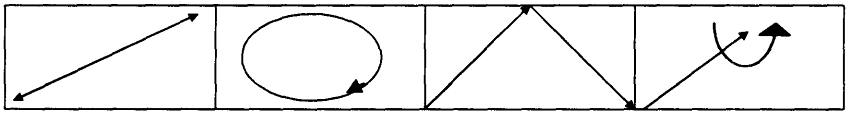


Figure 14. Different paths swept out by the robot.

There were two main noticeable sources of error for the robot's motion. The first was its tendency to drift from the pre-programmed path. When the same path was swept out multiple times by the robot, it would inevitably go more off course the more times it swept. This error occurs because the robot does not currently have a feedback control to compare the path it is taking with the path it is suppose to be taking. Having a feedback loop, like in Fig. 14, will solve some of the drift error for the robot.

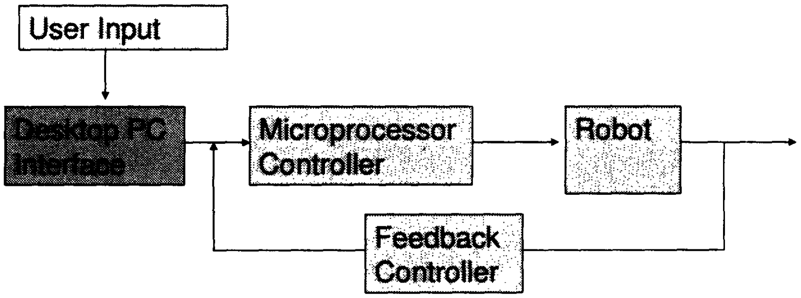


Figure 15. A block diagram of a feedback loop for position of robot on tabletop.

The second source of error was that it was hard to set up the robot in the same orientation each time, since there was no way to tell its orientation. This also contributed to the drift error because if the robot was not in the same initial orientation then it obviously will not trace out the same path. There are many solutions to this problem. Most of them include a known permanent fixture to which the orientation of the robot can be compared. This could be a starting pad that with mechanical or sensory markers to align the robot. It could be another type of sensor that can align the robot automatically.

5.2 Vertical motion of arm brace

The vertical motion of the arm brace was tested by setting the variable transformer to different voltages to supply different inputs to the motor. The larger the voltage supplied, the faster the motor would run. Similar to the motion of the base on the tabletop, the range of speed for comfortable arm movement for the vertical motion was also found to be 0.1 m/s - 0.5 m/s.

The biggest error in the vertical motion was the slipping of the pinion on the rack if too much downward force was applied to the arm brace. This error was due to the fact that the drawer guide had a little bit of give in the horizontally direction. Therefore the separation force mentioned earlier was able to put the inner frame away to cause the rack to become unmated with the pinion.

There are a few possible solutions to this problem. The first is modifying the rack and pinion setup so that there is no more wobble. This can be done be replacing the drawer slide with regular ball bearings. The radius of the pinion can also be increased to decrease the separation force since the force is inversely proportionally to the radius. The side of the frame with the guide can also be spring loaded so that the spring force is greater than the separation force.

The guide can also be moved to the same side as the rack and pinion, which will improve the system in several ways. The center of friction (which is the point at which when a force applied to a structure supported by bearings, there is no angular motion of the structure) of the brace is located close to the guide. When the rack was on the other side of the structure as the guide, it was not applying force through the center of friction and therefore was creating angular motion in the system which tilted the inner frame and created slippage. In a similar manner, the center of stiffness, another point at which no angular motion occurs is force is applied, is also located near the guide. By placing the guide on the same side as the rack, the force of the rack is brought closer to the centers of stiffness and friction to reduce the amount of angular motion in the inner brace. Finally, Abbe's principle states that angular errors are amplified by the distance from the source. This means that small angular errors caused by the guide translate into much larger errors by the time they reach the rack on the other side on the frame, which is another reason for slippage. If the guide is on the same side as the rack, the errors will stay small and reduce slippage.

5.3 Brace flexibility during arm movement

The effectiveness of the brace in allowing for arm rotation as the arm is being moved was tested by surveying the opinion of several subjects. The overall agreement was the foam and springs helped to support the arm while it was rotating. However, some subjects felt that the setup was a little on the stiff side. In order to determine the optimal configuration, a variety of different springs and foam should be tested. The springs should have varying spring constants and the foam different Young's moduli. In addition, the position and number of the springs can also be altered so that the springs attach from the top of the brace instead of the bottom.

Another solution would be to use a damper to provide the resistance during rotation of the arm instead of a spring. The resistance force of the spring increases linearly with distance away from the equilibrium position, meaning that if the patient's arm was more rotated, there would be a greater restoring force. However, this is not the ideal situation as it would be best if the arm had the same support in whatever position it was in. Dampers would solve this problem because their resistance force is proportional to the speed at which the arm is moving, meaning that the faster the arm is rotating, the more the dampers will resist and slow down the motion. This is actually more ideal because the patient should not be moving their arm too fast. In addition, adjustable dampers can be used so that the patient can set the damping ratio to match the support they need.

6 Future Recommendations

6.1 Short Term

The immediate next steps for the robot include gathering more data on subjects with the current prototype and making the changes mentioned above. More data needs to be gathered on consumer preference of the support and flexibility of the brace during yaw, pitch and roll. The current prototype should be made so that springs and their positions can be interchanged easily for subjects to test. A design with dampers instead of springs should also be tested. In terms of the motion of the robot's base, the next step would be to add a feedback loop into the robot's controller. Also, some way of aligning the robot's orientation, whether manually or automatically, should be implemented. The rack and pinion system needs to be modified so that the separation force between the two frames does not cause the pinion to slip on the rack. Fig 16 shows a diagram of a modified rack and pinion system with the guide on the same side. According to Saint-Venant's principle, the length of the linear bearing should be about 3 times its width, which is incorporated into the design. Also, only one bearing is used because of the difficulties in aligning the two bearings perfectly parallel.

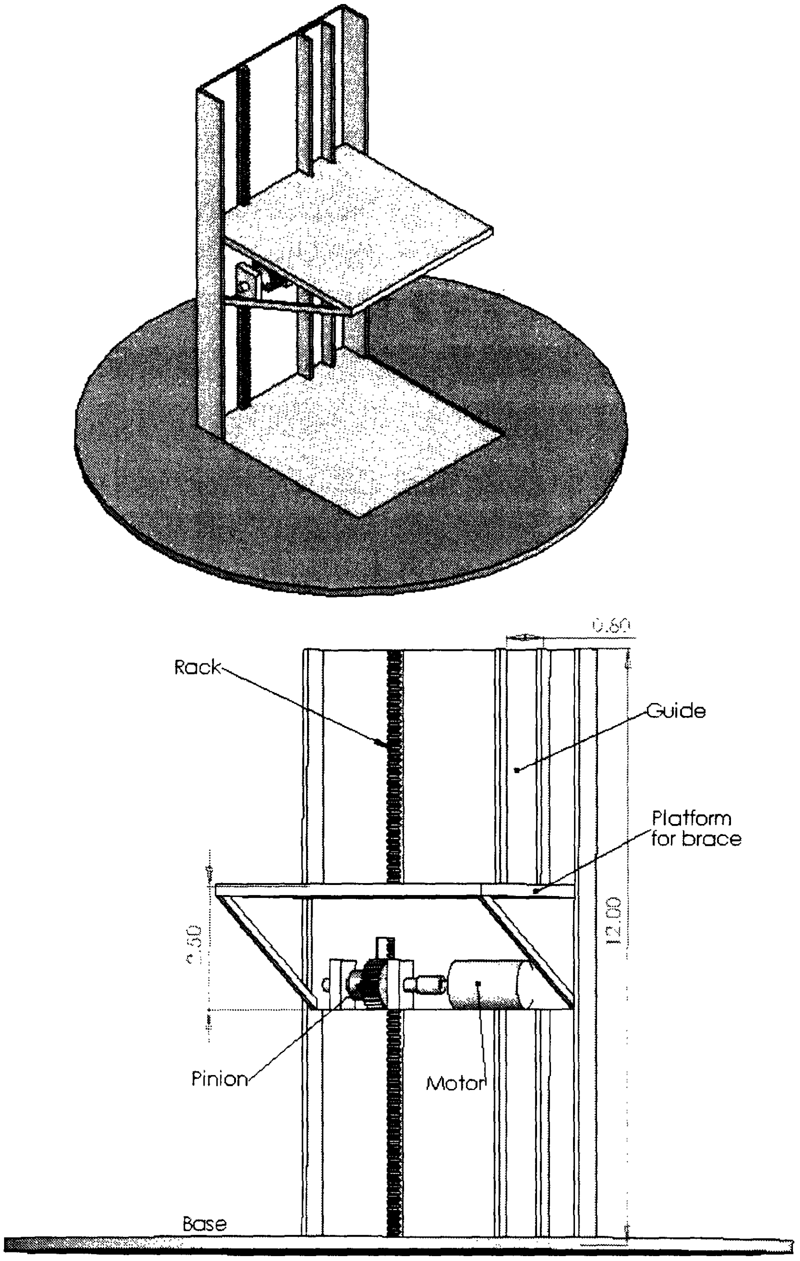


Figure 16. A full assembly of new rack and pinion system (above). A labeled diagram of system. (below)

A battery should be chosen for the application. Because the second generation of this project will also be a prototype, it would probably be better to use a NiCad battery since it is much more inexpensive but will meet the requirements. An attempt should also be made to replace the current motors with more optimal ones according to the specifications described above. It is important to note that these characteristics may also change as the design of the robot changes.

6.2 Long Term

In the long term, and as each level of prototyping is being completed, there are several main points to keep in mind. These points include allowing the robot to have an active-assist and active-resist mode, measuring of the user's progress and the cost of the robot.

The impediment in achieving the active-assist and active-resist of the robot is that the motors are not back-drivable so that a person with normal arm function would not be able to manually backdrive the robot and move it. There are a couple of solutions to this problem. The first is employing the same technology on the MIT-MANUS that allows for low intrinsic endpoint mechanical impedance for the motors. The second solution is to allow the arm brace to move in the plane of the tabletop freely from the robot. This can be done by suspending the brace with flexible supports. The patient can then move their arm in the brace and the base of the robot will "follow" the arm's movements. To achieve this, sensors will have to be put into place that can measure the arm's free movement in the brace. The supports will also have to be adjustable into becoming rigid again when the robot is in passive mode.

Measurement of the user's progress can be obtained by the same sensors described above. The robot can read and record data on the direction and force of movement by the patient over time for comparison.

A more detailed market study will have to be performed to assess the needs of the patients to determine the cost constraints for the robot. While the robot is currently fairly inexpensive, the addition of sensors and other mechanisms will complicate the robot and increase its costs. It will be important to know what patients want and are willing to pay for.

As it stands, the robot can go in a different direction of not necessarily aiding in rehabilitation but serving as a tool to help patients without motor function in moving their arms to perform simple tasks. With just the improvements mentioned in the "Near Future" section, the robot might serve this function. Someone else, or even possibly the patient depending on the user interface, can preprogram the robot to guide the patient in a task and then come back and reorient itself for the next time. In this case the patient will not have to make any movements with their arm and the robot will not need to have sensors or back drivability. With a simpler design and few components, the costs of such an aid may fall well within a patient's range.

7 Conclusion

In this project, the functional requirements for a tabletop robot for aiding in arm rehabilitation of stroke patients were determined through bench level testing and research of existing robotic therapy devices. The goal was to have a small autonomous robot be able to move a patient's arm in a given trajectory on a tabletop. The design that resulted was that of an arm brace mounted on top of a moving base. The base needed to be omni directional to accommodate all possible trajectories of motion of the arm, the arm brace needed to be able to be moved up and down in the vertical direction as well as be flexible enough to accommodate yaw, pitch and roll.

A first generation prototype was built along with Adam Kraft. Adam Kraft built and tested the moving base using a three-wheeled design employing TransWheels^{TM}. I used a rack and pinion setup with a variable voltage regulator to control the vertical motion of the arm brace and a foam and linear spring combination to allow for yaw, pitch and roll while still providing for support of the arm brace.

Testing of the prototype proved extremely valuable in refining the requirements of the robot as well as the proposed design. Issues that were discovered during testing of the robot included drift of the robot, the inability to orient the robot the same way each time, the slipping of the pinion on the rack if too much downward force is applied to the arm brace and the stiffness of the arm brace during yaw, pitch and roll. Several suggestions were made for possible solutions to the issues, all which are very feasible to implement.

The one big impediment in allowing the robot to achieve an active-assist and active-resist function for rehabilitation is the lack of back-drivability of the motors driving the wheels, which means the patient cannot roll the robot by themselves. Again solutions were proposed that are worth further examination to determine their feasibility.

If however, the solutions prove to be unfeasible, the robot might be a very useful tool for patients with limited arm motor function. With a few changes, the robot act as a guide to move a patient's passive arm along a preprogrammed trajectory to aid the patient in performing tasks such as reaching. Even if the robot is unable to match its initial goal, it has great potential to become a valuable asset to stroke patients with limited arm motor function.

7.1 What I learned

This design process was an excellent learning opportunity. The first design process I've gone through without the structure of a class or lab instructor, it has allowed me to see what my tendencies are and how they play out in the process. The most important thing I have learned is to perform bench level experiments and build mockups as early and as much as possible. The experiments and mockups should be well thought, but do not have to be perfect. The reason is that the feedback from testing the experiments and mockups as well as the process of physically building something is essential to the process. Theory and sketching alone can only accomplish so much and need to be supplemented by actual building. This is an important realization because I tend to want to have all the theory figured out and the designs drawn out before starting to build or experiment. Especially with prototyping where the first thing built is not the final, iterations of building and refining are crucial to the process. In future design processes, I will be more aware of performing hands on experiments along with theory.

Appendices

Appendix A: FRDPARRC Chart

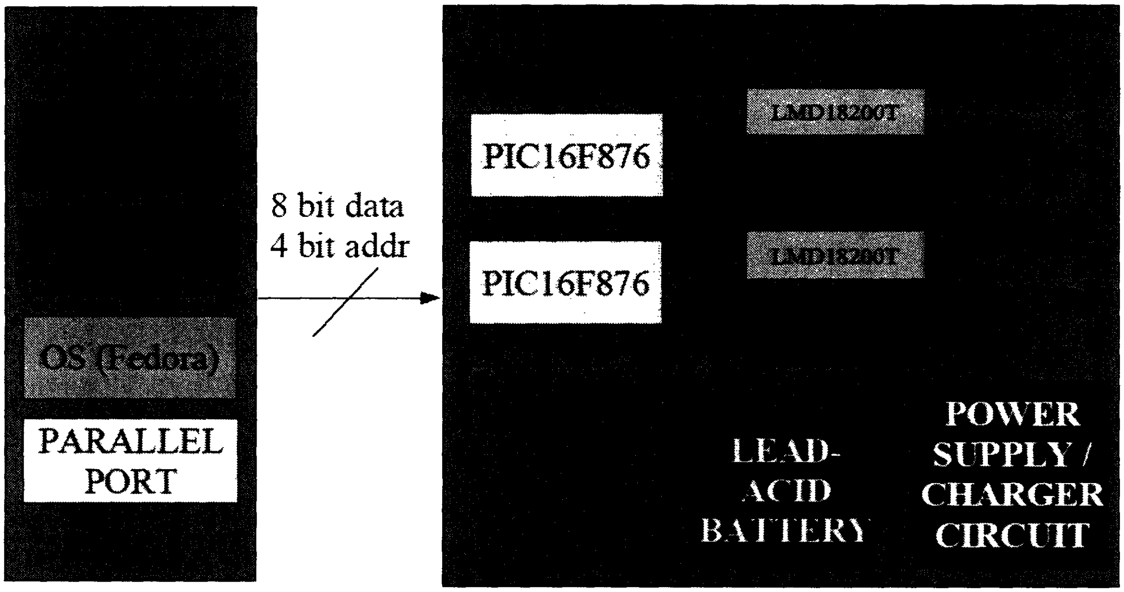
Functional Requirements	Design Parameters	Analysis	References	Risks	Counter-measures
Motion in X-Y plane (translational and rotational)	4-wheel drive 3-wheel drive	T=F*r T_s<friction P=Tw	2.007 lecture notes	Uses too much power Need large motors Costs	Use more motors? Lightening load on top
Motion in Z-direction	Rack/pinion Leadscrew Worm gears	T=F*r Mechanical ad	2.007 lecture notes Online motor suppliers	Backdriving motor Uses too much power Costs Safety	Use two motors Use frictionless guides to reduce force
Battery life lasts several years	Rechargeable batteries (NiCd, NiMH, Li-ion)	W=V*A	2.009 battery primer Online battery stores	High costs Short life cycle Size	Replace batteries more often
Comfort	Adjustability Conformity Support	Points of support & constraints Direction of flexibility	Previous robotic designs Ergonomics	Discomfort of patient	Repeated testing More flexibility
Future Considerations					
Measuring the patient's motion	Force sensors Displacement sensors		Online Catalogs		
Sensorimotor aid			Previous robotic designs		

Appendix B : Matlab Script for Sizing Motor

```
%Sizing robot motor
m=10;           %mass of robot, kg
g=9.8;          %gravity
Fg=m*g;         %normal force of robot on table

u=.75;          %coefficient of friction btw wheels and tabletop

r=.0508;        %radius of wheel, m
v=.5            %linear velocity of robot, m/s
a=.5            %linear acceleration of robot, m/s^2

T=Fg*u*r        %torque needed to overcome friction on table
T2=(Fg*u+m*a)*r     %torque needed during acceleration
w=v/r           %angular velocity, rad/s
p=T*w           %power of the motor, watts
rpm= w/(2*pi)*60     %revolutions per minute
```

Appendix C: Block Diagram of PC to Robot System

Provided by Adam Kraft.



Appendix D: Matlab Script for Rack and Pinion

```
function rackpinion

m=10; %kg
r_pinion=.0127; %m
g=9.8;

Fg= m*g
Tmotor= Fg*r_pinion

v_linear=.5; %m/s
w=v_linear/r_pinion
rpm=w/2/pi*60
```

Appendix E. Equations used in Rack and Pinion Analysis.

Inputs	
Pitch, P	P
Pressure angle, alpha (degrees)	α
Number of teeth on pinion, N	N
Tooth material	
Allowable bending stress, (psi)	σ
Tooth width, tw (in)	tw
Tooth Geometry	
Circular pitch (in)	π / P
Addendum, a (in)	1 / P
Dedendum, b (in)	1.2 / P + .002
Clearance, c (in)	.2 / P + .002
Tooth height (root to tip), (in)	a + b + c
Tooth thickness, tt (in)	π / (2P)
Tooth thickness at root, ttr (in)	tt + (2bc)sinα
Shear area, (in^2)	tt * tw
I/C at root, ICr (in^3)	tw * ttr^2 /6
Distance pitch line to root, (in)	b+c
Gear Teeth Strength	
Maximum tangential force to shear failure, (lbs)	shear area * (σ/2)
Maximum tangential force to bending failure, (lbs)	σ * ICr / (pitch line to root)
Maximum allowable tangential (rack) force, (lbs)	min of shear and bending forces