DESIGN OF A ROBOTIC EXOSKELETON ARM FOR REHABILITATION

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ABSTRACT

Stroke accounts for over 2,000,000 people who have chronic acute arm impairments. Currently the rehabilitation process for stroke involves a physical therapist manually moving the patient's arm, with no quantitative measurements for improvement. This problem extends to the fact that there are few technological devices available to assist in the rehabilitation process, even though it is largely mechanical by nature. Those devices that are available are often large, do not offer a full range of arm motion, are not portable, and not available to most physical therapists for clinical use.

The robotic exoskeleton arm is designed to fix most of these problems. It will be lightweight, give the patient full degrees of freedom in movement, and will give the patient more options in physical therapy. It will have sensors attached to the arm that will give the therapist quantitative feedback on the patients recovery, which should mean a speedier and more complete rehabilitation. In order to help the physical therapist, a virtual environment will conduct the

patient through exercises in a game-like fashion. This should not only make the rehabilitation process more effective and interesting, but also allow for variety in the type of the exercises as the patient improves, i.e., increased productivity of the rehabilitation.

KEYWORDS

Orthotic devices, rehabilitation robots, robotic exoskeletons.

1. INTRODUCTION

Stroke accounts for over 2,000,000 people who have chronic acute arm impairments. Currently the rehabilitation process for stroke involves a physical therapist manually moving the patient's arm, with no quantitative measurements for improvement. This problem extends to the fact that there are few technological devices available to assist in the rehabilitation process, even though it is largely mechanical by nature. Those devices that are available are often large, do not offer a full range of arm motion, are not portable, and not available to most physical therapists for clinical use.

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Past research into the rehabilitative robotic exoskeleton has been concentrated on the hand and ankle, and when dealing with the arm, work has been limited to the elbow. The computer model of the exoskeleton will incorporate three degrees of freedom to allow for a more complete range of motion. The computer model has been designed and built in MSC Visual Nastran, allowing for simulations of the arm in motion to be run, and for the collection of data pertaining to the stress on the arm, the applied forces on the lower and upper arm, velocity and orientation of the arm, as well as the force and torque exerted on the elbow while the human arm is taken through the therapeutic exercises.

The success of the simulations will hopefully result in an actual prototype exoskeleton arm being built. This should greatly improve the methods of stroke rehabilitation and help more people overcome stroke related arm impairments with greater speed.

2. BACKGROUND AND RELATED WORK

2.1 Cerebral Vascular Accident (Stroke)

Cerebral vascular accident (stroke) is one of the leading causes in severe disability in the United States. Over 500,000 people experience a new stroke every year, and there are over 2,000,000 people chronically affected by stroke. About 85 percent of stroke patients incur acute arm impairment, and another 40 percent of victims are chronically impaired. The techniques used in the rehabilitation of stroke victims is largely of a mechanical nature, and a typical rehabilitation session has an occupational therapist move the patient's hand through a series of simple tasks which include putting pegs in holes, drawing, or writing. The physical therapist will also direct the patient through simple exercises, such as stretching the arm or rotating the wrist. This is done in hopes that the movement will trigger previously stored motor programs, allowing the patient to remember how to perform certain tasks.

There are two main modes of rehabilitation that the physical therapist employs: active assist exercise and passive exercise. Passive exercise is when the physical therapists will move the arm through the exercises with no motor input from the patient. In active assist mode, the patient will initiate the movement, and if possible will complete the movement. However, if the patient is unable to apply the power necessary to complete the task, or the patient is moving in a direction that will not complete the task, the therapist will then help and move the arm in the correct direction.

2.2 Robotic Arms

One cannot discuss rehabilitating the arm with robots without first discussing robotic arms. These arms provide the biomechanical basis of the exoskeletons, and are some of the first ventures into making robotic orthotics arms.

The first computerized arm was developed at the Case Institute of Technology (now Case Western Reserve University) in the early 1960's. The arm was configured as a floor mounted four degrees of freedom exoskeleton. It was controlled with a head mounted light sensor that would trigger light sensors in the environment. Rancho Los Amigos Hospital and Stanford University continued this research, and developed the six-degree-of-freedom Rancho "Golden Arm" (Figure 1). The Rancho Arm was similar to the Case arm, but had no computer controls. It was also mounted on a wheelchair and was found useful by people with disabilities with intact sensation resulting from polio or multiple sclerosis (MS). The only problem with the Rancho arm was its lack of computer controls, as the seven tongue-operated switches made the control tedious and difficult to use. (Rahman *et al.*, 2000).

Figure 1. The Stanford/Rancho Arm (Rahman *et al.*, 2000**).**

Another prominent robotic hand is the Salisbury Hand. Developed at MIT, the Salisbury Hand is perhaps one of the more advanced robotic hands developed. Using three fingers, it can grasp and move items of all different sizes and shapes, ranging from a pop can to a circular ring placed on the outside of the hand**.**

2.3 Rehabilitative Robots

Though the rehabilitative procedure is largely mechanical, there is a surprisingly small amount of technology available to assist the physical therapist. The technology that is available is in the form of the "robotic arm." Not a traditional robotic arm, these robots, allow the patient to place their arm in the machine, and the robot will then lead the patient through selected exercises. The robots can measure force on arm, joint angles, and acceleration of the arm, as well as apply different forces to the arm.

There are several robot arms that are used in stroke rehabilitation currently. These include MIT-Manus (Hogan *et al.*, 1992), Palo Alto MIME (Mirror-Image Motion Enabler) Robot (Lum *et al.*, 1997), and the Northwestern Arm Guide (Reinkensmeyer *et al.*, 2000). Each of these devices approach the rehabilitative process differently, consequently using different design aspects, but still the address the issue of helping the patient relearn motor controls and techniques through controlled arm movement.

The Northwestern Arm Guide uses reaching as its target movement, as this is fundamental to many activities in everyday life. The reason for this is that the robot can then focus on relatively straight-line trajectories, allowing a single motor to control the movements, as compared to a multiple DOF robot. This allows for a simple and relatively inexpensive robot. The Arm Guide allows for passive and active assist modes of therapy, where it can assess tone (resistance to externally imposed movement of a passive limb), spasticity (a velocity-dependent increase in stretch reflexes), which is tested by manually stretching a muscle group with the patient relaxed, and incoordination (abnormal muscle synergies). (Reinkensmeyer *et al.*, 2000).

The Palo Alto MIME Robot takes the arm through six different motions, all limited to the horizontal plane for safety reasons. Optical encoders on the joints of the arm measure position and orientation of the forearm while a six-axis force/torque transducer measures force and torque on the arm. There two options for movement control. The first is to preprogram the movement into the computer and allow the robot to take the patient through the exercises. The second option for moving the arm is to slave the movements of the robot to the movements of the normal limb. (Lum *et al.*, 1997).

The MIT-Manus offers five degrees of freedom: two translational degrees for forearm and elbow movement and extension-flexion, abduction-adduction, pronation-supination for the wrist. Two 16-bit high-resolution resolvers will measure position and velocity of the translational motion, and redundant velocity will be measured with DC-tachometers. The robot is able to employ various firmness in the rehabilitation depending upon the patient's level of movement and strength. The workstation for the Manus (hand in Latin) will be of a video game design, making it easy to follow and use, since the prime target for the robot will be young handicapped children and adults (Hogan *et al.*, 1992).

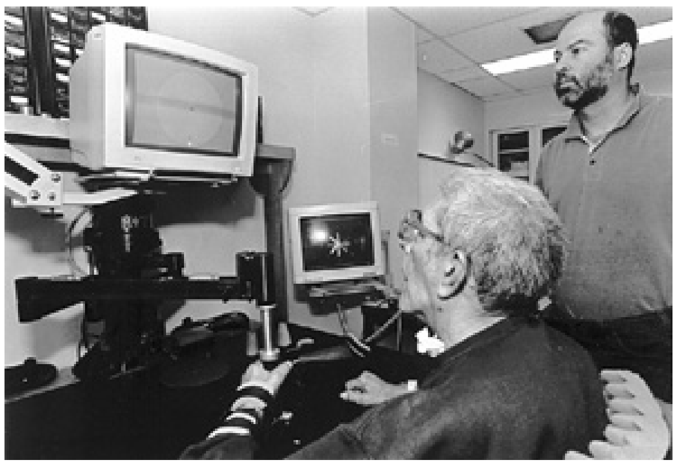

Figure 2. MIT-Manus (Hogan et al., *1992*).

Though not a rehabilitative robot, there has been a two-degree of freedom manipulandum designed to study human arm dynamics. The purpose of this manipulandum is to measure the forces given off by the arm during slight tremors of the muscle, especially the muscular causes of tremors. This is useful because it gives rehabilitative research a basis for human arm dynamics measurement, as well as a better understanding of the forces that are created involuntarily by the arm (Adelstein and Rosen, 1987).

3. ROBOTIC EXOSKELETON ARM

The entire rehabilitative system will consist of the robotic arm with sensors, a computer to collect data and provide a virtual environment, and the physical therapist.

3.1 Physical Design

The robotic exoskeleton orthotic device is the next step in stroke patient rehabilitation. In a way it is a combination of the traditional robotic arm and the current rehabilitative robots. The arm should have the ability to move almost exactly like the human arm, while at the same time have the ability to carefully guide the patient's arm through the required therapeutic exercises.

The exoskeleton should ideally have 7 degrees of freedom: shoulder abduction-adduction (2), upper arm rotation (1), elbow flexion-extension (1), forearm pronation-supination (1), and wrist movement (2). However, the movement of the wrist is often included in the design of the exoskeleton hand, and it would be redundant to include this in the design of the exoskeleton arm. (Bergamasco *et al.*, 1994) That reduces the degrees of freedom (DOF's) to five, which is much more manageable, since exoskeleton arm technology currently only allows for 6 DOF's (Remis, 1990). Also, in order to further simplify the design of the exoskeleton, the shoulder will not be modeled, due to the complexity in its overall movement, leaving only 3 DOF's: upper arm rotation, lower arm rotation, and elbow flexion-extension.

The exoskeleton will closely resemble an arm brace (Figure 3 and Figure 4) with servo motors powering the movement of all three degrees of freedom. There will be one motor at each of the elbow joints on the exoskeleton, and though pneumatic cylinders have been said to be a better option due to their light weight (White *et al.*, 1993), motors will allow for finer torque and velocity control. Servo motors will also be used to control the turning actions of the upper and lower arms.

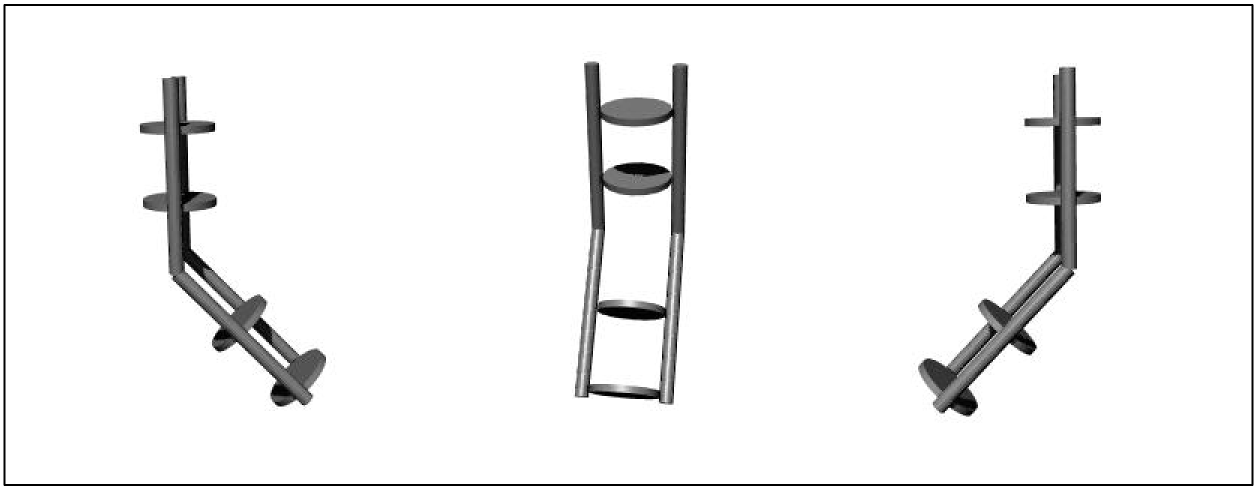

Figure 3. Base design of orthotic exoskeleton (the circular rings will have one large hole in the middle of each circle for arm, this was not possible due to software limitations).

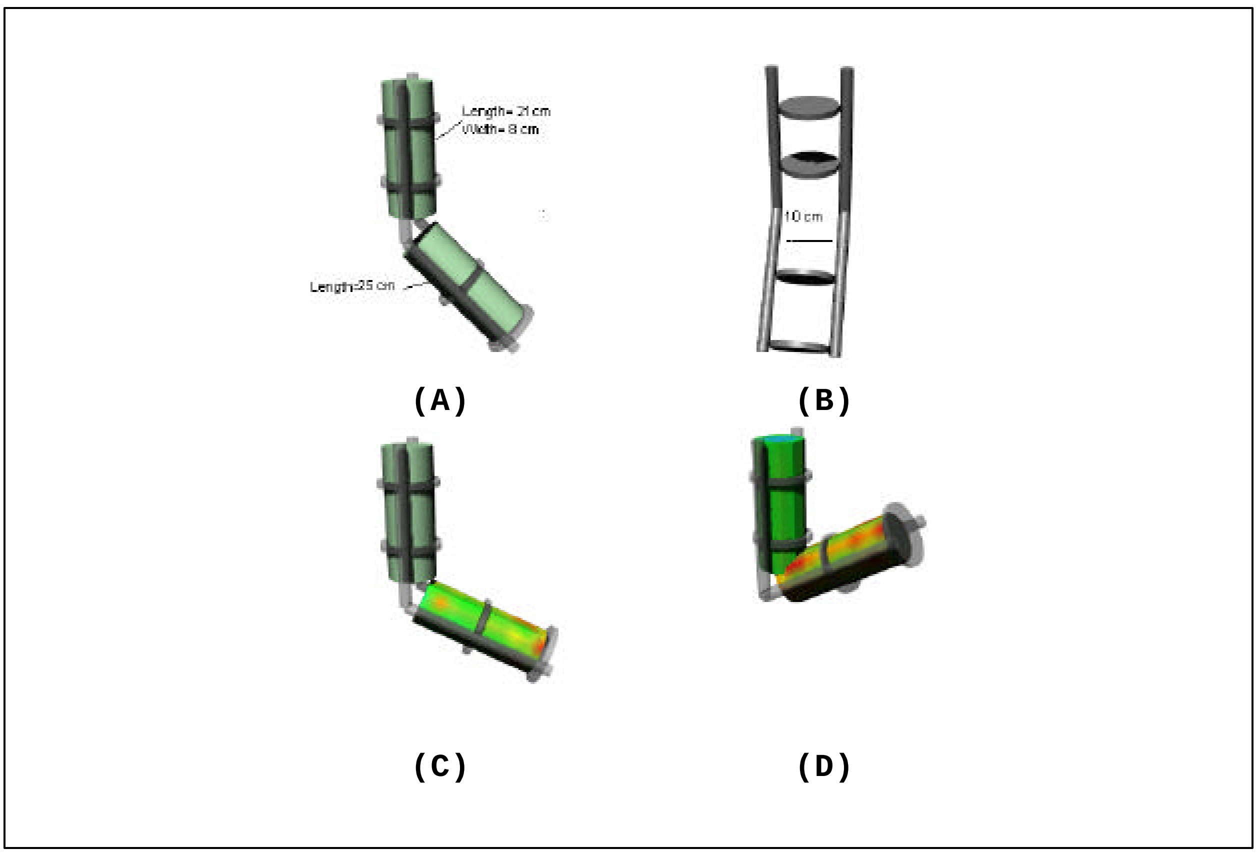

Figure 4. (A) Model of exoskeleton with arm and measurements (B) Model of exoskeleton with measurement (C) Simulation with only lower arm in FEA (D) Simulation with both arms in FEA

In order to determine acceleration and velocity of the arm, joint angles will be measured and calculated by the computer system. There are several options for measuring joint angles: Potentiometers, Hall effect sensors, optical encoders, accelerometers, conductive rubber (highly experimental), optical fiber, and cable tension sensors (Brown, *et al.*, 1993). Which type of sensor will be used to measure the joint angles has yet to be determined, but optical sensors (much like those in the optical mouse) will be used to track the position of the arm within the virtual environment. The robotic arm will also feature EMG sensors to measure muscle activity.

A key feature of this design will be the ability restrict the movements of the joints as shown in Table 1. Not only does this help the robot conform to the actual movement range of the human arm when healthy, it also restricts it, so that injuries from overextension do not occur.

Joint	**Degree of Movement**
Shoulder Azimuth	135
Shoulder Elevation	130
Upper Arm Roll	260
Elbow Flexure	135
Lower Arm Roll	215

Table 1. Degrees of joint movements.

3.2 Rehabilitative Modes

The rehabilitative exoskeleton arm needs to be able to adapt to the need of the patient, and if not by itself, then with the help of the physical therapist. There are four modes of operation that will be used by the exoskeleton:

Exercise Mode. The patient is passive throughout this mode of rehabilitation, which will primarily be used during the early stages of stroke recovery. The exoskeleton will take the arm through a series of movements, teaching the muscles and the brain how the basics of movement again. The measurements will focus on the EMG readings, to see how the muscle reacts to the movements. Forces will only be measured to ensure that they are not in excess.

Percent Assist Mode. This mode can work two different ways. The first method is that the patient will start the motion needed and the computer will then complete the motion for the patient. This way the patient can slowly begin to gain more movement in the arm. The other method of rehabilitation in this mode is that the patient will attempt to move their arm towards an object, real or virtual, and then if the task is not being completed correctly, the intelligent robot can then correct the movement for the patient.

Static Evaluation Mode. This mode is used to determine the progress of the patient by testing the strength of the muscles. The patient applies as much force as they are physically capable of at various fixed arm angles. The computer, using the data from the sensors, then calculates the strength of the patient's arm at each point.

Dynamic Evaluation Mode. In this mode the patient moves their arm with minimal, if any, help from the robotic exoskeleton. The main purpose of the exoskeleton in this mode is to take force and EMG readings.

3.3 Virtual Environment and Intelligent System

The virtual environment must incorporate two key design elements: the interface must be very easy to learn and use, and the virtual environment must incorporate an intelligent system.

The interface will be a series of different games that the patient can play. These games will have to be of a nature such that the patient must move their entire arm to succeed. This is easy enough to accomplish, since any type of movement on the computer with a mouse-like interface will require the entire arm to move if the cursor speed is slow enough. Since the robotic exoskeleton will not have the ability to move the hand away from the body or towards the body, the interface will have to recognize movements of the hand upwards and downwards. This can be accomplished using video cameras and computer vision recognition, which will allow the cursor on screen to move up, down, left, and right based on the movements of the arm.

One possible option for a rehabilitative game is 3D Pong. This game will utilize two dimensions of motion, and make the patient move their arm in ways that causes the cursor to move the entire area of the screen. The premise of the game is to hit the ball back and get it past the computer player. The skill level of the computer player would be adjustable, as would the ball speed. The level of movement the patient had would determine the levels of computer skill and ball speed.

The intelligent system is what will make the decision when and if to increase the difficulty level of the rehabilitative mode. It will make this decision based not only on the scores the patient has been getting in the game, but also based on the readings given back to the computer through the force, velocity, and EMG sensors on the arm. As the patient is able to increase the acceleration and velocity in the movements required by the game, the computer will be able to make the game more difficult to help the patient gain more control of their movements.

A virtual environment need not be created out of scratch. There are other virtual environments currently being developed, and two of these could easily be used with the robotic exoskeleton arm, and even in conjunction with the 3D Pong game based virtual environment, especially since a game such as 3D Pong is better suited to more advanced stages of rehabilitation. The two virtual environments are java therapy and virtual reality-based neuro-rehabilitation.

Java therapy closest resembles the virtual prototype mentioned above. It also is an existing virtual environment that has the capabilities of remote rehabilitation, where the patient and physical therapist do not need to be in the same room, or even the same country for that matter. The system uses a game interface, with patients playing Breakout, Othello, and Blackjack to name a few. Breakout requires the patient to move their and back and forth across the screen, whereas Othello and Blackjack are simple point and click games that require the patient to pick up objects and move them to another part of the screen. Users are required to log in on the internet in order to use java therapy, and this allows for a clinician to monitor the quantitative data from the virtual environment from anywhere in the world. Java therapy is also affordable, accessible and adaptable since it can use many different types of input devices, used the World Wide Web, and relies on Java applets, which are generally simple and easy to produce. (Reinkensmeyer *et al.*, 2001).

Virtual reality based rehabilitation is not nearly as affordable or accessible as Java therapy, but the interactivity and immersion of the technology make it an intriguing technology. This type of virtual environment would be focused on making “real world” exercises the key component to the patient’s rehabilitation, or making the patient better able to perform activities of day to day living. This could include opening a mailbox and getting mail, or pouring liquid into a cup. The virtual environment will take these actions, and, on the display, show the desired trajectory of motion, and overlay that with the motion that the patient is using. The patient can also see the motion done the desired way through a simulation before attempting it themselves. A study was done on the effectiveness of this type of rehabilitation, and subjects were 50% less likely to have errors in real world performance when their rehabilitation was complete. (Boian *et al.*, 2000).

4. SIMULATION

4.1 Methodology

Using Visual Nastran Desktop 4D, simulated exercises can be conducted on the arm. The brace will move the arm through these six exercises:

(1) Elbow flexion-extension
(2) Lower arm rotation
(3) Upper arm rotation
(4) Lower arm rotation followed by elbow flexion-extension
(5) Upper arm rotation followed by elbow flexion-extension
(6) Lower and Upper arm rotation followed by elbow flexion-extension

Each rotation will take one second simulated time, and will be rotated at 100 degrees for one simulation and 215 degrees on another simulation. This is the same for the upper arm, except that the second simulation will have a rotation of 200 degrees. The range of elbow flexion and extension will be conducted over a 9 second period of simulation time. The motor on each elbow joint of the brace will provide 31.4Ncm of torque, which will move the arm at 18 deg/s or the motors will provide –31.4Ncm of torque, which will move the arm at –18 deg/s (Table 2).

Time (s)	Torque (Ncm)	Angular Velocity (deg/s)
0	0	0
1	31.4	18
5	-31.4	-18
10	0	0

Table 2. Motor Control parameters.

The items that will be tested include: stress on the upper arm, stress on the lower arm, force on the elbow joint, torque applied to elbow joint, force on the arm at the wrist, angular velocity of the arm at the wrist, and torque on lower arm at the wrist.

4.2 Results

The stress test on the arm was the primary test to be conducted, with lower arm stress tested in elbow flexion-extension, lower arm rotation, lower arm rotation with elbow flexion-extension, and lower and upper arm rotation with elbow flexion-extension. Upper arm stress was tested in elbow flexion-extension, upper arm rotation, upper arm rotation with elbow flexion and extension, and lower and upper arm rotation with elbow flexion-extension.

The results show that higher stress in the arm occurs in two places: near the wrist where the contact point in the brace occurs and at the elbow. The stress in these areas is lowest in just elbow flexion extension, and only slightly higher in lower arm rotation. The stress was higher in the wrist and elbow in lower arm rotation with elbow flexion-extension and lower and upper arm rotation with elbow flexion-extension.

However, regardless of exercise several patterns of stress on the lower arm occurred. The stress on the elbow will be high initially and then as the initial movement of elbow flexion-extension begins, the stress levels are lowered. It seems that in the movement of the arm, the stress levels of the elbow are only high when they elbow is not in flexion-motion, though the stress does not lower as great when there is lower arm rotation involved in the movement. The stress in the wrist area also starts out at a higher level the majority of the arm, but as the initial movement starts the stress level spikes up, and then declines as the arm goes extends and flexes. The reasons for these patterns of high and low stress are the forces on the restraints where the stress measurements are taken.

The force on the elbow is highest before flexion-extension begins and then goes from 20 N to 15 N after 2 seconds (Figure 5), which explains why they stress at the elbow is higher at the beginning of the motion, declines in the middle of the motion, and ascends again at the end of the motion. With lower arm rotation and elbow flexion extension, the force starts out high, but declines about 3 N after 1 second (Figure 6). Unlike without lower arm rotation, though, the forces never go below 15 N, and stay at 21 N for 5 seconds during the middle of the arm movement. This is what accounts for the higher stress during lower arm rotation with elbow flexion-extension compared to just elbow flexion extension (Figure 7 and Figure 8).

The stress on the lower arm near the wrist is a result of the force on the restraint at the contact point between the arm and the brace. The initial spike in high stress correlates with the spike in force when the arm begins to move, and the high levels of stress during lower arm rotation with elbow flexion-extension as opposed to only elbow flexion-extension are due to the higher levels of force on the arm restraint.

The stress on the upper arm highest at the elbow, but unlike the lower arm, that was the only high area of stress. Since there were no forces being applied to any constraint on the upper arm, other than the elbow, the stress was relatively low. However, in the elbow, the stress was higher when the upper arm was rotated before elbow flexion-extension in comparison to when only elbow flexion-extension was used. This is due to the increase in overall force on the elbow during the upper arm rotation followed by flexion-extension of the elbow (Figure 9).

4.3 Discussion

The results in the simulation will truly only give an idea of how the patient's arm will react to certain movements in passive exercise mode. This is mostly for safety reasons, as excess stress on the arm and excess force on the joints will due more harm than good, which is counterproductive to rehabilitation.

The reason that no numbers were provided for stress data is due to the fact that the design of the arm is not entirely accurate. For one, since the shoulder is not modeled, forces are not going to be accurate for the upper arm, since this would considerable change the movements and exercises available to simulate. Also, for the stress numbers to be accurate, the bodies that are tested must be an extremely close match to an actual human arm, which in this case they are not. They are cylinders that are a very close material to steel in physical property. However, the areas of stress and relative stress levels will remain the same regardless of the material. Also, the design of the elbow and bodies is such that the cylinders rotate, as opposed to twist and deform, much like the human arm, which will lead to stress numbers that are irrelevant.

This though does not take away from the design process of the robotic exoskeleton, as well as the ability to simulate movements. If virtual prototyping can be done more accurately, this will save time and money when attempting to build the robotic exoskeleton arm, since it can be designed and tested before it is even built.

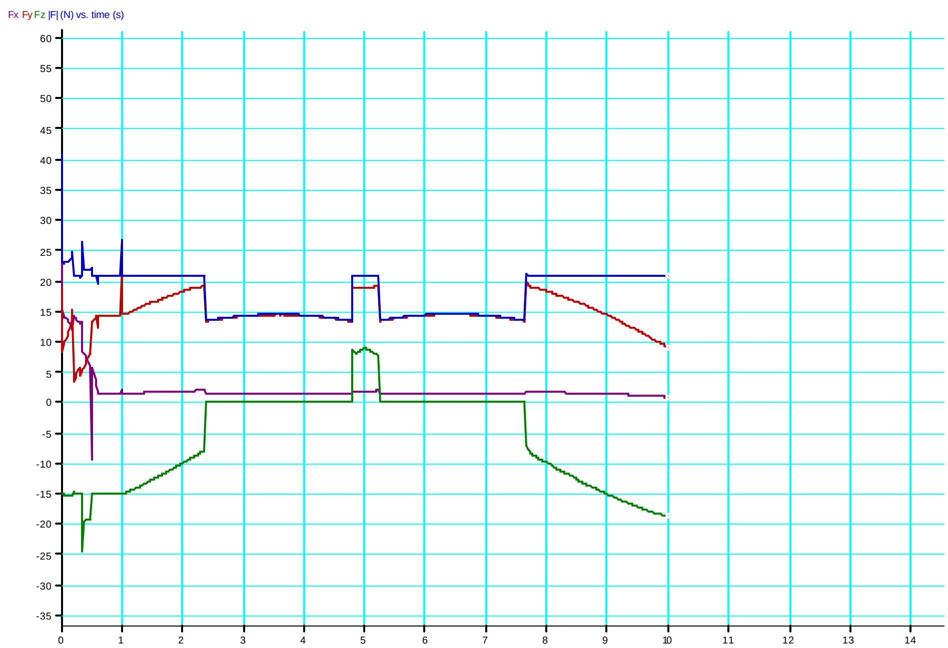

Figure 5. Forces on the elbow during elbow flexion-extension.

Figure 6. Forces on the elbow during lower arm rotation and elbow flexion-extension.

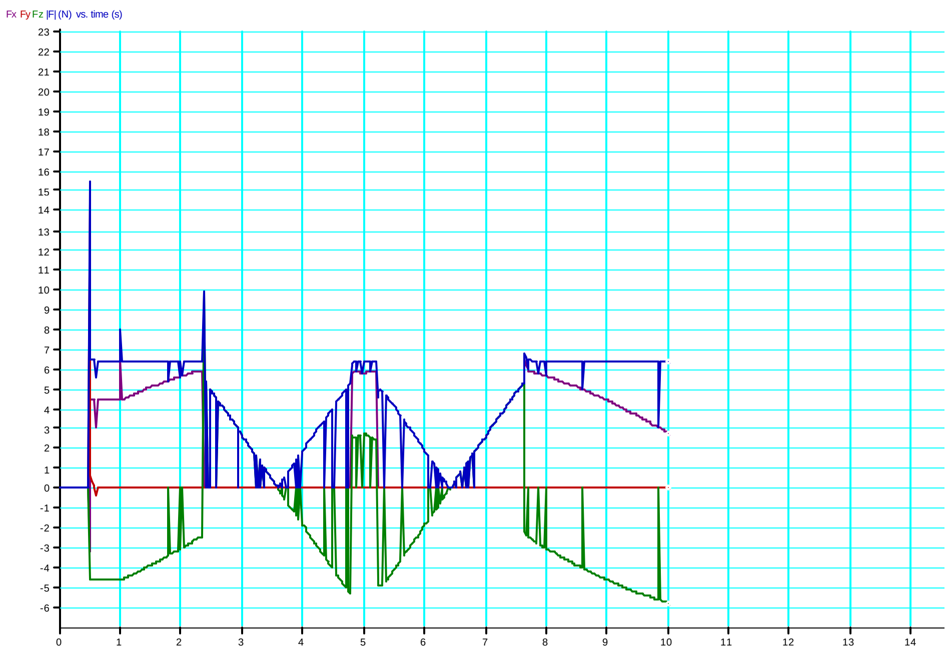

Figure 7. Forces on lower arm during elbow flexion-extension.

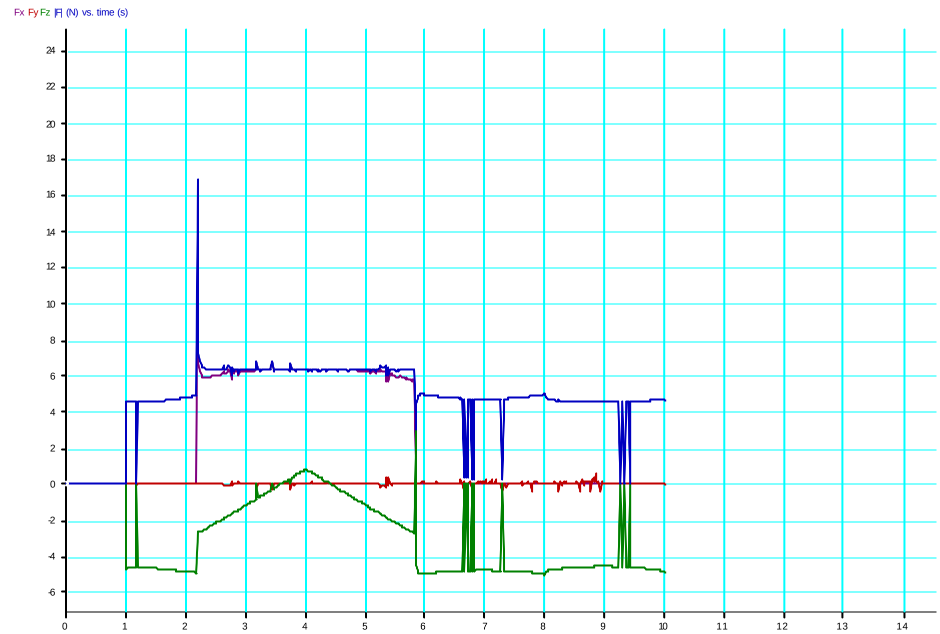

Figure 8. Forces on lower arm during lower arm rotation with elbow flexion extension.

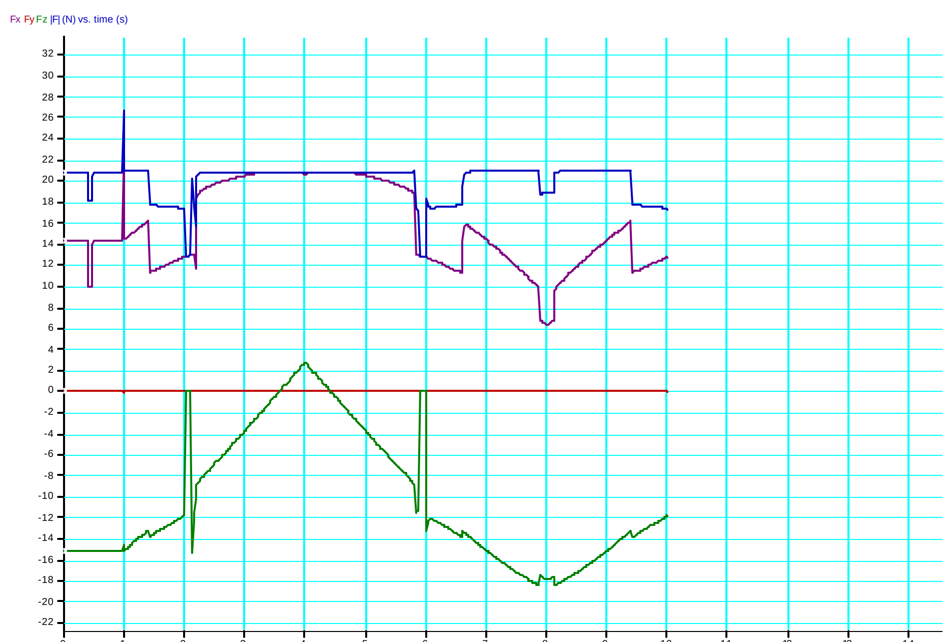

Figure 9. Forces on elbow during upper arm rotation followed by elbow flexion-extension.

5. CONCLUSION

The robotic exoskeleton arm has a very good possibility of becoming a reliable and widely used physical therapy tool. With the ability to take the device home and use remote therapy, the physical therapist will possibly be able to treat several patients at the same time, saving time and money for the patients. The physical therapist will also be able to make better decisions on the direction of the therapy with the help of the quantitative data that the arm provides, and the intelligent system that will analyze the data and make decisions on the rehabilitative level of the patient. Using this method, and with the advent of better virtual environments, this should further the overall goal of promoting a better understanding of motion recovery and therapy.

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