UC Santa Barbara

Volume 3 (2022)

Title

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Permalink

https://escholarship.org/uc/item/7zq4t6t1

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Publication Date

2023-04-01

Drawing Stabilization Robot for Stroke Rehabilitation

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Abstract

Stroke recovery is a difficult process, so there are many forms of robot-assisted therapy (RAT) that seek to make it easier for patients and physical therapists. However, machines designed for this type of therapy are often expensive unitaskers that limit their therapy assistance to only one part of a limb. We have developed a series of prototypes that have the potential to aid in drawing therapy for stroke rehabilitation and assessment, as drawing can engage every muscle group in the arm and is often used as a method of estimating limb and neural pathway function. Our current focus is refining a system of surface electromyography (sEMG) and internal motion unit (IMU) sensors processed via machine learning to quantify limb function and location in order to assist the user in creating their drawings. We believe this robot has the potential to be incredibly useful to artists with unsteady hands, physical therapists, and physical therapy patients.

1. Background

Stroke recovery is an exhausting, isolating, and expensive process. Physical therapy to recover limb function and neural pathways is the most expensive part of this process due to the need for frequent one-on-one appointments with physical therapists over the course of months or even years that may not be covered by insurance (Maciera-Elvira et al., 2019). In addition, many stroke patients prefer at-home rehabilitation whenever possible to allow for more schedule flexibility and to avoid the need to find transportation to what are often extremely distant specialist centers (Tyagi et al., 2018). The need for frequent one-on-one appointments can be reduced through robot-assisted therapy (RAT), which improves the quality of both group therapy and at-home physical therapy (Maciera-Elvira et al., 2019).

1.1 The Need For Robotic Physical Therapy

Many previous studies have utilized common stroke rehabilitation techniques to create robots to retrain motor movement in the upper limbs by utilizing TST and repetitive motions similar to what a physical therapist might assign as an exercise for a patient (Abdullah et al., 2011, Marini et al., 2017, Shahar et al., 2019, Castiblanco et al., 2020). TST can lead to muscle pain and fatigue, however RAT and non-RAT TST have been shown to result in the same level of pain and fatigue for patients (Shahar et al., 2019). In addition, RAT can include systems to monitor fatigue and pain. Patients also rate higher levels of enjoyment and interest in physical therapy when utilizing these robots, so the only cons in these robots come from their common design traits (Shahar et al., 2019).

For stabilization and ease of calibration, these systems are often large and heavy so the position of the exoskeleton or robotic interface is easily known (Castiblanco et al., 2020, Shahar et al., 2019). This leads to increased costs for consumers in both purchasing the additional bulky casing around the robot as well as creating a space for such personalized gym equipment. In addition, these heavy systems are incredibly difficult for patients to set up at home and can be very confusing (Tyagi et al., 2018).

Robotic physical therapy systems also usually deal with a single joint to simplify their control schemes (Castiblanco et al., 2020, Shahar et al., 2019). This means most RAT TST devices only utilize specific muscle groups in a specific part of the body. However, most people in stroke recovery are attempting to strengthen neural pathways in entire limbs, so RAT for multiple muscle groups can take up a huge amount of space and too much money for at-home usage throughout all of recovery to be feasible. All of these considerations have led to a market where only physical therapy centers and the few who can afford to buy, store, and replace such customized devices are able to utilize them.

1.2 Drawing Therapy

Drawing therapy is effective because it requires the coordinated and deliberate use of several muscle groups together. In fact, the steadiness, active range of motion, and spatial awareness required to draw a circle have led to the process being used as a common metric of stroke rehabilitation (Krabben et al., 2011). Increased circle size can be linked to increased active range of motion, as multiple muscle groups must be fully engaged to create a large shape (Krabben et al, 2011). The roundness of the circle is connected to both hand stability and coordination of muscle groups, as uncoordinated muscles lead to very eccentric ellipses (Krabben et al, 2011). Creating a robot that can automate this test would allow assessments to be conducted at home or in group settings, reducing the frequency of physical therapy sessions, allowing check-ins to be conducted online, and creating more data for physical therapists to monitor recovery between sessions. All of these effects would greatly reduce the costs of physical therapy for patients and create better quality remote health-care.

Drawing therapy can also help with the psychological issues that can come with a stroke by aiding patients in creative expression and teaching new skills (Reynolds, 2012). Many stroke patients are frustrated with their sudden loss of fine motor control, so providing an avenue to gradually regain control where patients can see visible progress helps ease their concerns. Stroke patients often feel isolated and have identity issues due to their loss of motor function and difficulty with the coordination necessary to engage in old hobbies (Krabben et al, 2011, Reynolds, 2012). Drawing and other forms of expression in a group setting can help mitigate these symptoms by providing community and helping the patient develop new hobbies. These hobbies in turn can help motor function as the repetitive and precise motor movements necessary to create art can improve coordination and aROM. Additionally, many artists and professionals who want to draw steady straight lines or curves without using software in a digital medium may benefit from a device that would aid in this task.

1.3 Our Design

There are no commercially available assistive devices designed to aid in drawing therapy due to the complexity of predicting both motion and the physical location of the hand to ensure images are drawn as intended, however, it has been proposed that this could be resolved by utilizing surface electromyography (sEMG) sensing, internal measurement units, or similar sensors (Bi et al., 2019). Similarly, there are no commercially available robots designed to collect data during circle drawing tests, a common way to determine the active range of motion and recovery of stroke patients (Krabben et. al., 2011). Through our complex controls scheme, we hope to continue to develop a robot with a high enough prediction accuracy, at a marketable cost, to eventually create a robot with the potential of aiding physical therapy centers, stroke rehabilitation patients, professional artists, hobbyists with unsteady hands, and professional craftsmen.

We propose a design for a robot that combines sEMG sensing, internal measurement units, and drawing therapy techniques to assist in physical therapy of stroke patients with upper limb weakness. This robotic physical therapy will strengthen neural pathways for motion of the entire arm, providing a way for circle drawing tests to be accurately conducted and drawing therapy to be less frustrating at home. Our design aims to be compact, affordable, and accessible for at-home usage, allowing users to draw with assisted-as-needed technology that will incorporate feedback on their task-specific training (TST), while they attempt to improve their active range of motion or quantify their recovery process.

2 Arduino Prototypes

In 2021, we created a series of Arduino robot prototypes as proof of concept for this idea. As part of a course, these initial prototypes were created under extreme budget and time constraints. However, this also means that a final product will likely be affordable for the average consumer; we calculated that our final prototype's components only totalled a cost of $69, with the potential for a total of $34.39 each in small batch production. 2 Arduino prototypes are on display in Figure 1.

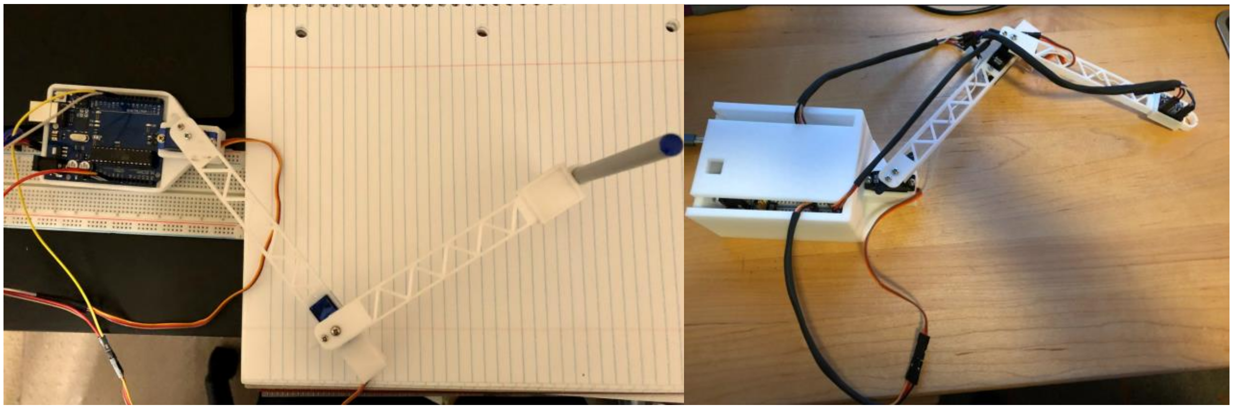

Figure 1: Left: The first working prototype with full range of motion, pen holder, and exposed Arduino board. Right: The final version of the Arduino prototype, with sturdier arm and complete casing to protect the board and internal power supply.

2.1 Hardware

Due to the initial budget constraints, our initial prototypes were created with Arduino components and 3D printed parts, as we had access to these from prior coursework. The robot consisted of three main sections: the circuit board, the servo motors, and the 3D printed arm.

Our initial circuit board was an Arduino Uno, chosen due to its versatility with hobbyist parts, its utilization of the C++ programming language which we were familiar with, and the fact that we already had access to it. We 3D printed a case for the board to protect it and act as a weight to ensure users could not easily knock the arm over. The purpose of this component was to store code, process the input from our sensor scheme, and anchor the rest of the robot. In addition, we added an internal power supply to this prototype to increase portability.

The servo motors are the method through which the robot stabilizes the user's motion. We used two metal sg90 servos with analog feedback, as this servo model is very cheap, hardy, and can read position while allowing for a large range of motion. When the servos are not preventing movement, they rotate freely, sending positional data such as location and acceleration to the circuit board in the process. However, when the sensor scheme detects abnormal movement, the board sends a signal to a servo to lock and provide resistance to the user, reducing movement while acting as the joints of the robotic arms.

The 3D printed arm was designed with a reinforced triangle lattice for a combination of strength, ability to organize wires, and reduced material cost. It has a full 360 degree range of motion due to the two actuating joints of the servos, allowing users to draw large circles. On one end of the arm is a pen holder made of 3D-printed natural flex filament which allows the arm to grip a pen, pencil, or marker in a large variety of sizes. Various improvements were made to the arm to increase stability, provide a wider range of writing utensils, and reduce sagging in response to issues caused by the arm's length.

2.2 Software

Arduino utilizes a form of the C++ coding language to input, process, and output data. While C++ as a programming language is excellent for AI, Arduino Uno boards have very limited RAM memory, meaning they process data very slowly. This means that by our choice of hardware, our software design had very limiting parameters to take into account. Therefore, our focus in creating this AI and the rest of the prototype's software was to streamline the logic needed to reduce movement. Our code simply took in the accelerometer data from the servo motors, determined if there was a large enough change between the previous reading, and the current reading, to necessitate a system reaction, which then determined which servo(s) should lock to reduce the movement and carry out that action.

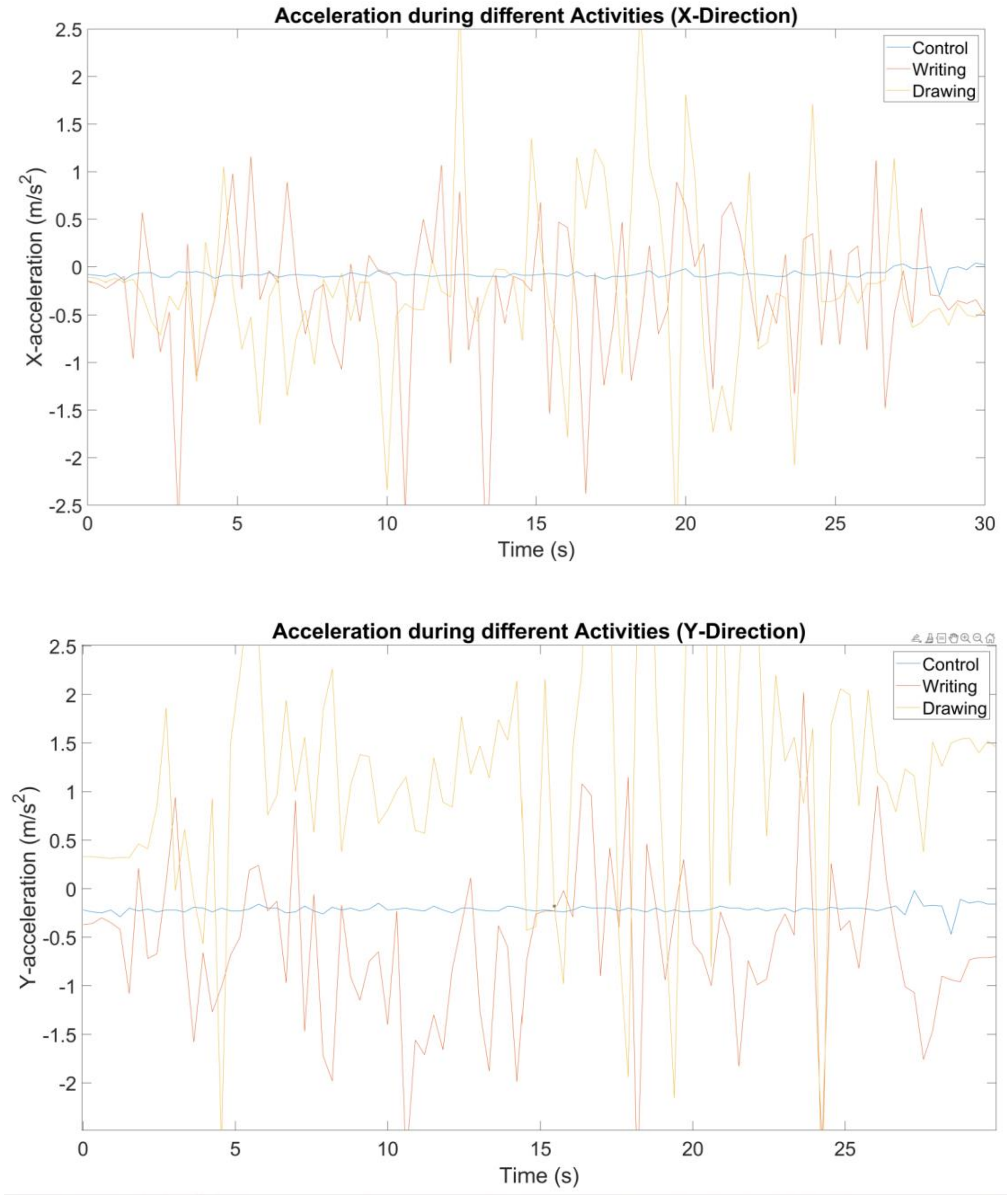

Figure 2: Accelerometer data captured during activities used to calibrate the software. The blue line represents the control of drawing a straight line, while red represents a writing activity and yellow represents a drawing activity.

Figure 2 displays the data we collected to determine optimal locking requirements, in which we recorded the acceleration of the robot's servos in both the x and y directions. From this data, we were able to determine that the normal range of motion of the robot during small controlled movements involved acceleration less than 1 m/s^2. Since our initial task was to create a robot that would be able to steady lines, we set our code to establish a direction where movement was unhindered (along the axis of the line) and an axis where the locking servos would hinder movement perpendicular to the other. Then, we tested how the servo locking impacted movement, settling on a limiting acceleration of 0.5 m/s^2 as that was able to greatly reduce the human-made oscillations during feasibility testing while ensuring normal movement still felt smooth.

3. Raspberry Pi Prototype

This is the prototype we are currently working on. The main hardware changes are switching the old Arduino board for a Raspberry Pi, as well as using a more robust design of the 3D printed arm and casing. Additionally, we are in the early stages of adding additional sensors to the user's arm to track their movement directly. These changes were caused by or in-turn caused software changes such as an improved AI that processes the increased information and a switch from C++ to Python for the coding language.

3.1 Hardware

Our new circuit board is a Raspberry Pi 4, which is a single board computer (SBC) rather than a microcontroller like an Arduino. We chose to switch our processing unit from a microcontroller to an SBC because they are more reliable, are powerful enough to run operating systems, and can compute much faster than microcontrollers (Álvarez et al., 2021). We also 3D printed a new case to hold the Raspberry Pi PCB, as it is much larger than the Arduino Uno. These upgrades will make future software development feasible.

In addition to the new board, we have incorporated two additional Raspberry Pi Pico microcontrollers which input sensor data from the user’s armbands. We chose these microcontrollers for the armbands because they work better with sensor schemes, are capable of bluetooth communication with the PCB, and are some of the smallest inexpensive boards available (Álvarez et al., 2021). These two armbands will be placed near the wrist and inner elbow, allowing for an additional six degrees of sensing through their monitoring of sEMG, rotation, and acceleration through internal motion units and sEMG sensors.

3.2 Software

The software running on the Raspberry Pi is based in Python rather than C++. The main benefit of this is to improve the user experience as well as the readability of the code. When using an Arduino and C++, the servos must be calibrated every time the device is powered on, which increases startup time. With a Raspberry Pi and Python, the calibration code is modularized, running only on the initial startup. Once run, the calibration saves data to a JSON file which can be read the next time the device is booted. All servo and sensor settings are also written in the calibration code and imported by the main script, which greatly increases readability. However, due to the Raspberry Pi’s lack of an analog-to-digital converter (ADC), a Raspberry Pi Pico is required to read analog position data from the servos. The Pico is a microcontroller running MicroPython, and the code saved on it is a simple script that checks the servo position. When required, the Pi sends a request to the Pico for the servo positions, transmitted over USB serial connection. Overall the Python code greatly simplifies the process of testing/prototyping, as well as provides functionality for all future upgrades, such as AI or a display/user interface.

4. Future Directions

We are very excited to continue to develop this robot, as we believe we now have access to all of the hardware and resources we need to fully realize our design parameters.

4.1 Full sEMG Integration

Due to supply chain issues, we were unable to start working on our sEMG integration until extremely recently. Our main future goal at this point is to fully integrate our sEMG sensors and internal motion unit armbands, allowing us to track the arm movements and fatigue of the user in order to predict future movement and suggested times to take a break.

4.2 Improved AI

This new system will require an AI run on our Raspberry Pi to take in the information from the armbands and process it simultaneously to the user's muscles taking in the same input. Future development in this area will focus on the speed of the data transfer, AI calibration to process the inputs, and creating a system to determine fatigue level from input.

We also have plans to implement multiple drawing modes. Currently, our robot only stabilizes linear movement, however, we are looking into creating additional modes to stabilize curved motions and guide users through predetermined motions. We anticipate that the curved mode will allow for much greater professional functionality, as precise arc drawing already involves the use of multiple tools such as compasses or protractors. Programming the robot with predetermined motions will not only allow it to guide users through tracing activities that might be designed to work on specific muscles, but will also allow the robot to collect data on tracing accuracy if the user traces the shape without the servo’s locking-mode on.

4.3 Future Testing and Design for Accessibility

So far, all of our testing has been for feasibility—to determine if the robot works as intended and has the main elements it needs to achieve our goals through further development. Now that we are fairly confident that we have everything we need to broadly meet our standards, our focus will begin to shift towards testing and redesigning the robot with the intended users in mind.

Since this robot is designed primarily to aid stroke rehabilitation patients, we have many plans to ensure our user experience (UX) in general is accessible to our users. We must make sure that the UX is comfortable, simple, and intuitive. Our initial steps to improve UX include designing the armbands to not impede movement as opposed to some slightly more accurate methods, to use adhesive sEMG sensors instead of needles to avoid unnecessary pain and medical risk, and to be easy to put on even with limb instability. We have plans to incorporate large, textured buttons as the power and modes switches to make it easier for users to access different functionality and a small touch screen to provide feedback. This is because older patients tend to have difficulty with complicated touchscreen controls, so we want to ensure that the device will have different levels of digital intractability based on user comfort (Tyagi et al., 2018). In addition, we will work to make the setup of the robot as simple as possible for the user.

Through the continued development of this robot and the prioritization of potential patient needs, we hope to create a robot that will act as an elegant solution to various patient and provider needs for the stroke rehabilitation industry, in addition to providing a useful new tool to professionals and hobbyists alike.

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Acknowledgements

Many thanks to our research advisor Professor Glenn Beltz for believing in this project and ensuring we had access to the resources we needed as we worked through supply chain issues and growing pains. We would also like to thank Professor Tyler Susko for creating the challenge that inspired the initial prototype, the UCSB ASME club for connecting the team, Professor Amanda Stansell and Professor Daniel Frank for their assistance with the grant proposal and technical writing process, and Lauren Mathis and Lindsey Crocker for additional biomedical advice.