Upper Limb Rehabilitation for Patients Recovering from Stroke: Low Income Setting

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Executive Summary

The Poovanthi Institute of Rehabilitation is a rehabilitation facility that focuses on occupational and physical therapy for individuals who have undergone strokes, brain injuries, and spinal cord injuries. Our goal as an ME 450 project team is to address the rehabilitation gap that stroke patients face in low-resource settings, specifically in southern India. We are seeking to achieve this goal by developing a solution that will provide stroke patients with the tools and resources necessary to regain the ability to perform activities of daily living (ADLs) after they return home from the clinic. In India, the incidence of stroke is 1.44 million per year and it is a leading cause of long term disability. A lack of resources and reduced access to at-home treatment hinders recovery and places increased stress on caregivers and the families of patients. The core functional requirements of our design include that it must be able to help users improve shoulder, elbow, and wrist range of motion and strength, improve their functional prehensile grips, be adjustable to fit a wide range of patients, and it must be safe, meeting CDSCO criteria for low-risk device approval. Requirements of medium priority are that the solution should satisfy user comfortability, be affordable to end users, able to keep users interested, able to be transported, easily understood how to use, able to be maintained at home, and able to withstand expected usage conditions. To begin the concept generation process, each team member ideated forty concepts individually, yielding two hundred in total. We then narrowed down this number to five by utilizing a filtering process in which we eliminated ideas based on duplicates, feasibility, fulfillment of requirements, and the potential for development. From those five concepts, we employed a Pugh chart to select the alpha design of an interactive slide board, finding it performs best in terms of cost, ability to take home, strengthening ability, full arm accommodation, and preference to current treatments. The interactive slide board concept was further developed into an alpha design using CAD. The design consisted of a slider arm, attached at a pivot point that would slide through a 180 degree arc. With an adjustable handle and variable weight on the slider arm, this solution allowed users to train prehensile grips as well as range of motion and strength for the wrist, elbow and shoulder. Analysis was performed to assess the risk of tipping, effect of friction, and material selection. A prototype of the alpha design was constructed, serving as our build “beta” design. Several aspects of the alpha design were changed, the hanging weight was removed and replaced by a brake, the slot was replaced with an arc, a suction cup was added, wheels were attached to the slider arm to contact the arc and slots for door hooks were added. By utilizing engineering analysis, we tested the effectiveness of the door hooks, suction cup, wheels, and brake. We also used this prototype to verify our requirements and specifications. Through testing of this prototype, we found new challenges to address and iterated on our existing design to produce a final “gamma” design, which we manufactured and presented at the design expo. Preliminary testing to assess the ease of use of the device was conducted and future plans for validation in the form of clinical trials were outlined. The strengths, weaknesses and risks of the final device were assessed and the broader context of this project was considered.

Abstract

This project seeks to address the rehabilitation gap between in-facility care and at-home care that people recovering from strokes in low-income settings face, with an overarching objective of developing a device to improve on current at-home rehabilitation methods. After an in-depth process of concept generation and selection, we selected an alpha design which we were able to prototype in order to test aspects of our design. With the results from these tests, we redesigned our solution to address the problems revealed through testing and constructed a final product based on this design.

Introduction and Background

Worldwide, stroke is the second leading cause of death and annually affects 15 million people[1], [2]. When someone experiences a stroke, half of their brain loses blood flow and oxygen, which can result in cell death within minutes [3]. This cell death prevents the brain from sending signals to the muscles on the opposite half of the body which can cause hemiplegia, paralysis on half of the body, or hemiparesis, weakness, or difficulty to move half of the body [4], [5]. The upper limb on the affected side of the body will experience this weakness as well as, difficulty in planning arm movements (apraxia), tightness in muscles (spasticity), looseness in muscles (hypotonia), a joint becoming fixed (contracture), and swelling [6]. These effects can cause a loss in strength, coordination, movement, and sensation making it difficult to perform activities of daily living, like feeding, cleaning, and dressing themselves which negatively impact their quality of life. Afterwards, stroke patients can have very different levels of movement capability. Some patients regain movement abilities and are able to walk within a few weeks whereas others – about 20% – are unable to ever walk without assistance [7]. Stroke recovery can take six months to over a year to work through until the patient is back to their former ability.

We are working with the Poovanthi Institute of Rehabilitation and Elder Care, a center in southern India that provides physical and occupational therapy for adults with disabilities, through their Chief Medical Officer Dr. Shibu, and Lucy Spicher, a University of Michigan graduate student who worked at Poovanthi this past summer as a design ethnographer. We seek to design an affordable, at-home, upper extremity rehabilitation device for people recovering from stroke in order to address the rehabilitation gap that those in low income settings face during stroke recovery. We have also been assisted by the University of Michigan's Stroke Rehabilitation Program's Director, Dr. Edward Claflin, and one of their occupational therapists, Bethany Blanchard.

The resources that a patient has access to can greatly affect the outcome of their rehabilitation. Patients in low- and middle-income countries are over three times more likely to die from a stroke compared to those in high-income countries [8]. People with lower socioeconomic status also tend to be at a higher likelihood of having increased risk factors for stroke. Those in low resource settings often are not getting the best immediate care when having the stroke which then can make recovery harder as well.

Physical and occupational therapy are two very important factors in a patient's recovery as they work to build brain-muscle connections to regain functional use of the affected side of the body [9]. In therapy, patients are guided through exercises to regain movement and range of motion in their joints with the help of therapists. Once they have gained most or all of their range back in a joint, they will begin working to strengthen those muscles with weights, resistance bands, or other devices [10]. Depending on the stage in the patient's recovery, they practice activities of daily living (ADLs) like washing, feeding, and dressing themselves with the goal of working towards full independence or as close to it as possible.

In the US most stroke recovery starts in an inpatient or subacute rehabilitation setting with multiple sessions of therapy a day and around-the-clock care. This can last from a few days to a few weeks [11]. After inpatient care, patients return home but are able to continue going to therapy multiple times a week in outpatient care for as long as needed to continue to work to regain full body autonomy [12]. Patients may also stop choosing professional care and try to rely on normal everyday tasks to help them recover further [10].

Upper limb rehabilitation therapy usually starts with passive exercises, where therapists are moving the arm and hand through different movement patterns to gain range of motion and build a mind muscle connection. Once the patient is able to, they will begin moving their arm through these same movements to begin strengthening the connections and muscles themselves. Common arm movements are shown in Figure 1 below [13].

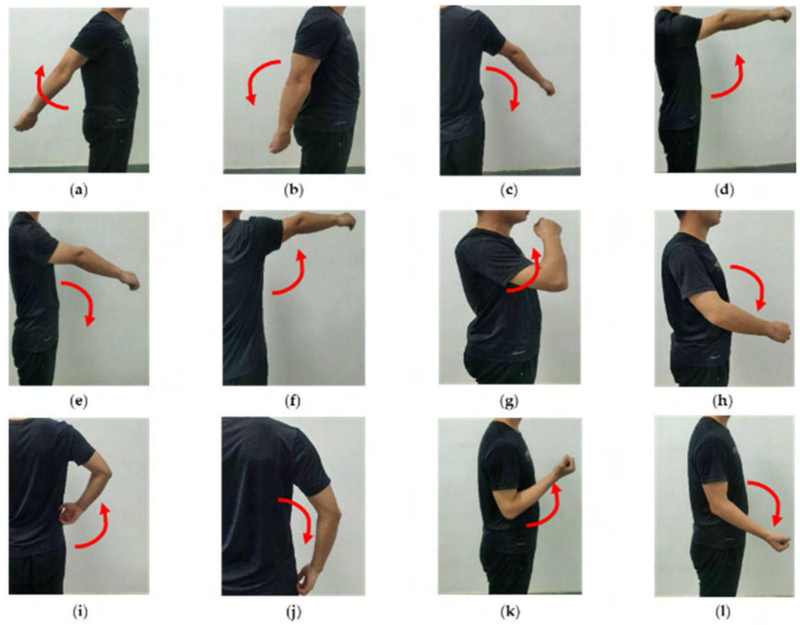


Figure 1. This figure shows a variety of different movements that are performed during upper limb rehabilitation. (a) posterior extension of shoulder; (b) shoulder backstretch return; (c) shoulder adduction; (d) shoulder anterior flexion; (e) shoulder forward flexion return; (f) shoulder abduction; (g) feeding action ; (h) feeding return action; (i) pant move; (j) pant return move; (k) elbow flexion; (l) elbow extension

As they gain more control of their upper limb they strengthen their muscles further by adding resistive elements such as weight or exercise bands [10]. An important aspect of upper limb rehabilitation is regaining the function of the hand to hold onto specific grips [14]. There are six main prehensile grips that are worked on, which are shown below in Figure 1 [15].

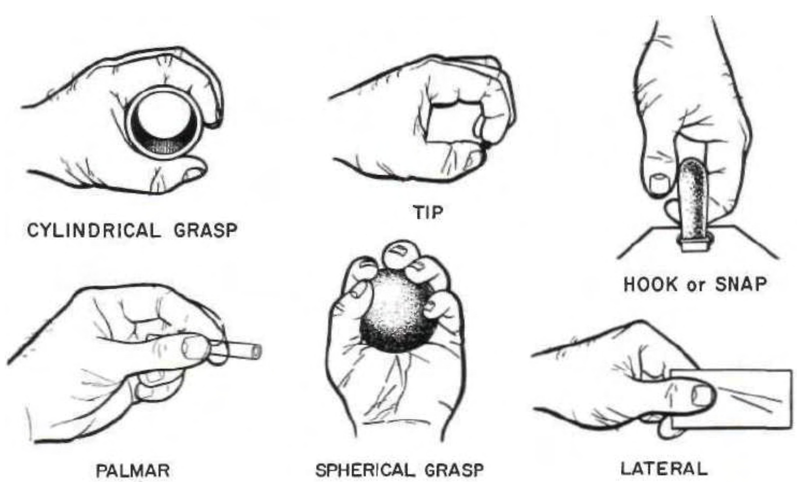


Figure 2. Diagram illustrating the six functional prehensile grips. These grips are cylindrical, tip, hook, palmar, spherical, and lateral [15].

At Poovanthi Institute of Rehabilitation and Elder Care in India, all patients are inpatient and 70% of the residents are recovering from a stroke [16]. While there, they usually have one or two caretakers who are either family members or minimally trained homecare nurses. Patients have three, two-hour therapy sessions a day between occupational, physical, and speech therapy. The therapist-to-patient ratio at Poovanthi is 1:12, which is much lower than the recommended 1:7 ratio [17]. These factors can lead to some patients getting a quality of care that may not be as high as it could be with the recommended ratio. On top of this, it can be a financial burden on the families as they pay out of pocket. Sometimes patients have to return home and get a loan to come back. With these financial issues, it is common for patients to leave the facility after they have begun walking and have a functional gait. Once they go home they are usually unable to return for outpatient visits and often do not continue their rehabilitation exercises either because they lack motivation, find the exercises too hard, or are too busy to try to incorporate them into their schedules. About 20% of patients who leave Poovanthi get weekly calls from the facility's social workers who check in on them and instruct them to do further exercises in hopes that they continue to improve [14].

Because patients leave as soon as they achieve a functional gait, they often leave before regaining full use of their arms and hands. With their upper limb deficiencies, patients may find it really hard or even impossible to do ADLs like making food, doing laundry, getting dressed, or cleaning themselves. Lacking these abilities not only makes day-to-day living difficult but can also stress them out at a time when they already are having emotional struggles. One study found that three months after a stroke, 30% of people were struggling with post-stroke depression [18]. This is the gap our group is addressing and why our group is looking to design low-cost upper limb rehabilitation equipment that patients can be taught to use in the clinic and then take home to further progress to their maximum potential. We are aiming our product to focus on patients who already have movement and some range in their upper limb joints at the request of Dr. Shibu [14]. Specifically, patients who score at 3- or higher on the Manual Muscle Testing (MMT) scale, which signifies being able to move freely against gravity with minimal support [19].

There are currently a lot of products that are designed to help with upper extremity rehabilitation after a stroke. At the more expensive end of these therapies are complete robotic exoskeletons that guide patients through movements as they play games such as the Armeo Power [20]. At slightly lower prices – but still much too high for Poovanthi patients to take home – are electronic devices such as the Saebo gloves or the CanDo Pedal Exerciser, both of which are used in the clinic [21]–[23]. Finally, products that would be in a comparable price range for our product and are meant for at home use are things like exercise bands, kids toys, and silly putties that come in different strengths [24]. To increase the strength of their arms, patients are told to lean on their arms at certain angles and bear weight on them. The extra weight helps to stretch the hand but this can be a safety risk because since they do not have full control, they may fall or push the joint too far, resulting in injury. Table 1 on the next page shows the different techniques and devices used for upper limb rehabilitation and the different criteria we took into consideration with green signifying it passed the criteria and red signifying that it did not.

Table 1. Benchmarking Analysis

	Low-Cost	Works Full Arm and Hand	Progress Levels
Armeo Power [20] 			
Music Glove [25] 			
Pedal Exerciser [22] 			
Exercise Bands, Toys, Silly Putty [26] 			
Dough, Rubber Bands and Weight Bearing Arm Stretches			

From the table above it can be seen that none of these devices or techniques satisfies all three of the criteria for our product's use. Some devices are too expensive, others do not rehabilitate all of the joints, and others do not show progress. Our goal is to create a device that can fulfill all three of these main criteria as well as meet the safety guidelines set out by the CDSCO for low-risk medical devices in India.

Design Process

There has been a multitude of design processes used so far in the development of our solution. Our first steps were heavily based on the University of Michigan's ME Capstone Design Process Framework because that is the process we had the most knowledge of. The first step of this process is defining the problem. This follows a problem-oriented design process. Since our team did not have extensive knowledge of medical devices, stroke rehabilitation, or the efficacy of certain solutions at Poovanthi, following a solution-oriented design process would have not met our requirements as accurately and kept us open to unconventional or unique solutions. As we met with our sponsor and resources, we were given a very open-ended problem. We were told the many different needs of the Poovanthi Institute and patients, and that our solution for upper limb rehabilitation could be accomplished by improving current therapy techniques or enabling more people to continue therapy when they left, in whatever form would be the most impactful. This open-endedness led to some fluidity in the scope of our problem definition within the DR1 period. When conducting preliminary research on the topic of stroke and stroke rehabilitation, we were also able to learn about the varying conditions patients can be in during recovery. This helped us form our requirements from what was identified as important for rehabilitation or critical for improving quickly. These design requirements have changed throughout our work. Along with these changing needs and requirements, our process naturally turned into an iterative process, becoming a hybrid of stage-based and activity-based processes. The process we have followed could be considered to be an abstract approach. The most similar process to our work is outlined as Ehrlenspiel's four-stage abstract design process, where some of the first stages include clarification of the problem, a search for the hypothesis, and selection of the hypothesis [27]. The feedback loops between these stages illustrate the process we followed to continuously update our requirements as we engaged our stakeholders further and keep our specifications design-independent. Eventually, we landed on a working problem statement for us to clearly move forward by focusing on the enabling of therapy for patients after being taken care of in the Poovanthi Institute. As we learned more about our problem and about physical therapies involving stroke rehabilitation, it was important for us to focus on the problem and not the solution, while we continuously updated our information and worked in an iterative fashion, which is why we followed the design processes we did.

Moving forward, we are going to utilize verification and validation according to the ME Capstone Design Process, similar to the waterfall method outlined by the Medical Devices Bureau [27]. Since our problem and solution is very heavily intertwined in the lives of people and not purely a technical challenge, it is important that the solution not only meets the specifications set earlier in the design process, but also is validated in that it answers the needs of patients and our stakeholders. This design process is important to us because it ensures that verification and validation do not happen solely at the end of the design process, but that we continuously keep in mind how well it fulfills our requirements and specifications. This is ultimately in the pursuit of helping the needs of our stakeholders and developing a solution that fills the gap we are targeting in stroke rehabilitation.

While going through our testing and verification process with our build design, we exposed a number of issues. In an effort to address these concerns, we iterated upon our design in a piecemeal manner in order to find solutions to address each individual problem.

Design Context

When developing a solution for upper limb stroke rehabilitation it is critical to consider the context that influences this project. In order to make a positive social impact, our team must consider the cultural, social, and environmental contexts of this project so that we are equipped with the necessary background to confront the challenges we face.

Global, Social, Cultural Context

The Poovanthi Institute of Rehabilitation has clinics located in Madurai and Chennai in Tamil Nadu, India. The World Bank classifies India as a low-middle-income country [28], meaning India lags behind high-income countries in terms of wealth and development. This has an overall negative impact on the burden of stroke in the country, as 89% of all stroke-related disability-adjusted life years occur in lower-income, lower-middle-income, and upper-middle-income countries [29]. India and other lower-middle-income countries face challenges in stroke care such as unreliable access to primary stroke care as well as lack of uniformity and standardization of secondary and tertiary stroke care (rehabilitation) [30]. Technology is being increasingly leveraged to overcome these challenges, this puts our project in the global context of the worldwide effort to leverage technology for healthcare solutions. The cultural context that must be considered relates to caretaking norms. In India, family members often play a significant role in rehabilitation of individuals with disabilities [16]. Thus designing a solution that is able to be understood by both the user and caretaker is necessary. The social context that underpins our project is the goal of enabling independence for individuals with disabilities so that they can perform the activities necessary to function in society. This aligns with our goal of enabling stroke patients to regain function of their upper limbs to perform activities of daily living.

Public Health, Safety and Welfare

Public health, safety and welfare are other concerns that are crucial to take into account. Our project seeks to address the public health issue of the lack of at home rehabilitation for upper limbs after strokes. We will ensure that our solution solves this problem and thus makes a positive impact on public health and improves the welfare of stroke patients in low income contexts.. In order to do this we must ensure that our solution is safe. The requirement that our device must be able to be used safely is classified as high priority, demonstrating our commitment to the safety of our device.

Stakeholders

Our project includes a variety of stakeholders with varying degrees of power and interest. Stakeholders that are high in interest and high in power include Dr. Shibu, Professor Sienko, the Poovanthi Institute of Rehabilitation, and Lucy Spicher, we will work closely with these entities, meeting regularly to inform them of our progress, gain insight, and provide resources. Stakeholders that are high in interest but low in power include people recovering from stroke, local communities in Southern India, Healthcare professionals, the William Davidson Institute, the UM Global Health Initiative, and Patient Advocacy Groups. We plan to contact these groups to share with them any relevant information. Stakeholders low in interest and low in power include NGOs, Global Health Organizations, Health Insurance Providers, and Competing Rehabilitation Organizations. We plan to keep these entities informed about our project, although based on our timeline for the semester we do not expect our work to directly affect any of these entities during the span of our project. Entities that are high in power and low in interest include regulatory agencies, Poovanthi employees, and competing industry organizations. The Poovanthi Institute of Rehabilitation and its patients would be the primary stakeholders who benefit from a successful solution developed by this project. Stroke patients in other locations and healthcare professionals could benefit if our solution is scaled beyond Poovanthi. However, Poovanthi employees and caretakers could be negatively affected as their already established methods of rehabilitation must be changed if a new solution is introduced. We have employed various methods to engage our stakeholders throughout the design process. Our team has met several times with the project sponsor Dr. Shibu to gain insights into how to align our project with the needs of Poovanthi. We have also met with Professor Sienko on a bi-weekly basis to update her on our progress. We have engaged healthcare professionals such as doctors and physical therapists through meetings to answer questions relating to stroke rehabilitation. We have also engaged the William David Institute through our section discussion with Pavan Kittagaly and Claire Hogikyan in which we received feedback on the best ways to commercialize our project.

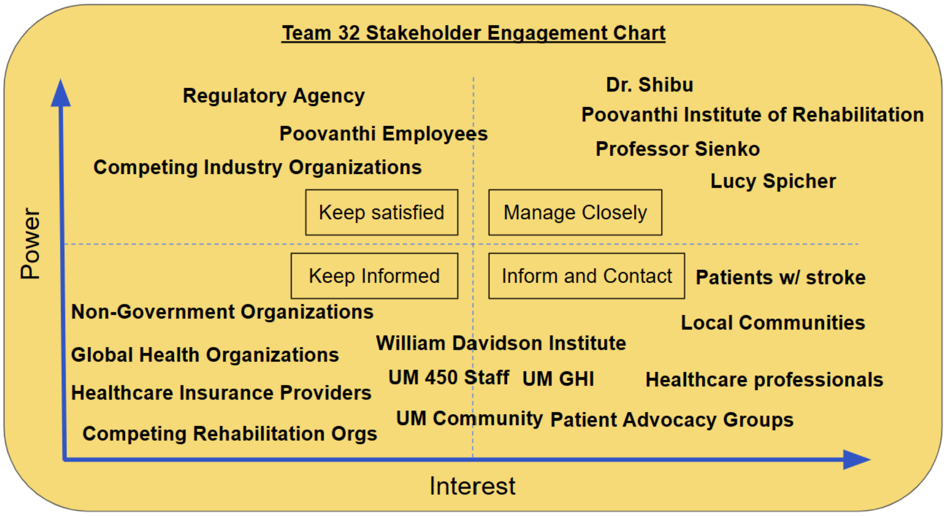


Figure 3. Stakeholder Engagement Chart. This chart shows all our most important stakeholders placed on two axes, the y-axis represents the power to influence the project, the x-axis represents interest in the project. Each quadrant includes an engagement goal applicable to stakeholders in that quadrant.

Social Impact

The goal of this project is to make a positive social impact on communities in Southern India by providing a solution that will rehabilitate the upper limbs of stroke survivors so that they can regain function and perform activities of daily living. Because the Poovanthi Institute functions to rehabilitate patients back into society, we believe that our sponsor places a high priority on social impact. Social impact is most likely prioritized above environmental or educational concerns, but behind profit, as Poovanthi is a private business. The priority of social impact will ensure that our solution can be produced at a cost that can be afforded by Poovanthi patients. This will ensure that our solution will have the widest accessibility and thus the greatest social impact.

Intellectual Property

Each member of the group was required to grant a non-exclusive license to the University of Michigan, granting them the ability to use our solution to further the Global Health Initiative. This also means that the university can earn and keep revenues from our project invention, provided those revenues fund further work toward the Global Health Mission. However, each student still retains ownership rights of any project invention. Based on our research and benchmarking to date we have yet to find any similar products with intellectual property we might infringe upon.

Environmental Context

Our project fits within the environmental context of healthcare organizations placing increasing emphasis on sustainability [31]. The production of our design in the context of the class will be sustainable in that we will utilize methods that do not emit a significant amount of pollutants such as milling, lathing, water jetting, and 3D printing. However, if our project design is scaled and manufactured on a large scale, this will inevitably result in emission output due to the generation of energy using finite resources such as fossil fuels. Our design could be made more sustainable by utilizing materials that when disposed of will decompose within a reasonable time or can be recycled. We could also use manufacturing processes that result in the least amount of emissions and pollution. However, prioritizing sustainability in design and manufacturing will most likely increase the cost of producing a solution.

Ethics/Power Dynamics

The team anticipates the dilemma of balancing the sustainability of our project with the need to produce a cost-effective solution. The way we plan to manage this dilemma is to ensure the most sustainable practices and materials are utilized while not exceeding our budget. Another possible dilemma we might face is balancing the aim of promoting independence for stroke patients with the risk of creating a dependency on rehabilitation technology. A way to manage this is to design our solution to gradually reduce dependence over time. Our ethics as a team that align with what is expected of us by the University of Michigan and future employers include honesty, respect, and responsibility. Differences in values may include the fact that personal ethics are more individual-centered, considering the immediate impacts on oneself, however, professional ethics consider impacts on a larger organization or community. Furthermore, privacy is an ethical concern that is valued highly in professional rather than personal contexts. In terms of power dynamics between the various entities involved in the project, the sponsors Dr. Shibu and Lucy as well as Professor Sienko have the ability to influence our project design as they possess the power to make strategic decisions affecting the project's scope, goals, and timelines. These people also have a varying degree of influence over Poovanthi patients, the UM Global Health Initiative, and the William Davidson Institute due to their connection to these stakeholders. End users exert power over the project by providing insights and feedback regarding the project's design and functionality and through the acceptance or rejection of the final product. Each team member exerts power based on his expertise, skills, and contribution to the project. Those with specialized knowledge can influence decision-making more than those without that knowledge. Furthermore, our group possesses implicit power over the end users because we ultimately decide on the final solution. Although we are designing a product with the end user needs in mind, ultimately our solution is designed to fulfill the requirements of the ME 450 course. This is an inherent problem that cannot be eliminated fully, only minimized. We will minimize this issue by meeting with the project sponsors Dr. Shibu and Lucy Sphicher often, to assess that our solution aligns with end user needs.

Information Sources

At the beginning of the semester, our group met with librarian Sarah Barbrow where we learned effective approaches to information gathering. The methods of information gathering that worked well for us included reviewing literature regarding existing solutions, relevant technologies, and best practices for rehabilitation. Seeking advice from experts in the rehabilitation field such as physical therapist Bethany Blanchard and Dr. Edward Claflin offered us insights into the rehabilitation process which helped guide the scope of our project. Furthermore building and testing our prototype allowed us to gather real world data on the performance and usability of our solution. Challenges associated with information gathering included lack of access to end users, since our end users are patients at the Poovanthi Institute in India, we did not have any opportunity to interact with them. Another challenge was that as the project progressed, our requirements and specifications changed, shifting the scope of the project, requiring the need for additional information.

User Requirements and Engineering Specifications

There are a number of requirements developed for our project that are divided between priority levels. For each of these requirements, we have been working to identify specifications. As can be seen below in Table 2 on page 12, we have eight high-priority requirements that cover the most important aspects of our project.

Range of Motion Requirements

Our first three requirements came directly from our primary sponsor, Dr. Shibu, and highlight the main features our project must have [23]. These are our requirements to help users improve their range of motion for their shoulder, elbow, and wrist. The basis of each of these three requirements is that our device must allow users to move through their entire range of motion so as not to impede or hinder their recovery. This directive came directly from Dr. Shibu, and the rotation values tied to these specifications are based on CDC findings on the average ranges of motion for different joints [32].

Prehensile Grips

Our next requirement is that our product must be able to help users to improve their functional prehensile grips. As can be seen in Figure 1 on page three, the full range of functional prehensile grips is made up of the cylindrical, tip, hook, palmar, spherical and lateral grips [33]. Dr. Shibu specifically highlighted the need for users to work on all of these grips and the lack of ability for users to do so with their current rehabilitation techniques [14], [34].

Measure Joint Angles

The next requirement that we have is that our product must be able to delineate the full ranges of motion into distinct levels. When patients leave the rehabilitation facility, they often do not continue their rehabilitation and those that do often complete their exercises incorrectly or overextend themselves and cause further injury. To help mitigate those concerns, Dr. Shibu requested a way for users of our device to know when they reach their desired angle of motion, leading to our addition of this specification [14].

Strengthening

During one of our earlier meetings with him, Dr. Shibu stressed the importance of allowing users to build up their strength while completing their desired motions, so our product must be able to incorporate some sort of variable weighted or resistive component [14]. We later spoke to an occupational therapist who told us that the most weight we would need to incorporate into our device would be 15 pounds [10].

Accommodation

The next high-priority requirement we have is that our product must be adjustable and able to accommodate our intended users. Since the demographic of people who suffer strokes is so broadly encompassing, our first accommodation specification is that our product must be able to fit users between the 5th and 95th percentiles in India. Since our device needs to be able to support rotation about the wrist, elbow, and shoulder, our device must accommodate users from the lowest anticipated wrist to grip measurement to the highest anticipated shoulder to grip measurement. For that reason, we have specified that our device be able to accommodate from the 5th percentile for women's wrist to grip measurement, which is 2.31 inches, to the 95th percentile for men's shoulder to grip measurement, which is 28.94 inches [35]–[37]. The other specification for this requirement is that our product be able to accommodate users who can score at least a 3- on the MMT scale, meaning it can accommodate users who have at least half but not yet full range of motion against gravity [19]. Based on our discussions with Dr. Shibu, this is the level that we can assume patients will have reached by the time they leave the clinic and return home [14].

Safe for Users

Our last high-priority requirement is that our product be safe and hygienic. The regulatory body for medical devices in India is the CDSCO, so our product must meet their criteria for approval, and we are aiming for our device to meet those criteria under the category of Class-A (low-risk) devices. Since our device is intended to be implemented and used in India, we feel that if it is approved as a low-risk device by the CDSCO, then it can be reasonably deemed to be safe for our users. Our specification for this requirement is derived from the major components of this CDSCO classification, namely that our device not be intended to come into contact with injured skin, not channel or store substances, and not modify the composition of substances [38].

Table 2. High Priority Requirements

Requirement	Specifications
Able to help users improve shoulder range of motion	Allows for total range of motion (0-180° abduction, 0-60° extension, 0-180° flexion, adduction 180-0°, external rotation 0-90°, internal rotation 0-70°, horizontal abduction 0-45, horizontal adduction 0-135)

Able to help users improve elbow range of motion	Allows for total range of motion (flexion: 0-135°, extension: 135-0°)
Able to help users improve wrist range of motion	Allows for total range of motion (Supination: 0-90°, Pronation: 0-90°, Wrist flexion: 0-80°, Wrist extension: 0-70°, Radial deviation: 0-20°, Ulnar deviation: 0-30°)
Able to help users improve their functional prehensile grips	Capable to grip: cylindrical, tip, hook, palmar, spherical and lateral
Able to measure joint angles for users during exercises	Able to delineate angle measures between 0°-180° with increments of 5°
Able to help users strengthen their motions	Allows for variable loads from 0-15 lbs
Able to accommodate users	Allows for radius of rotation for patients up to 95th percentile: 2.31 to 28.94 inches Able to accommodate users scoring at least a 3- on the MMT scale
Able to be used safely	Meets criteria for CDSCO Approval to be Class A: Is not intended to 1) come into contact with injured skin, 2) channel or store substances, or 3) modify compositions of substances.

In addition to our high priority requirements, we have seven medium priority requirements as well, which can be seen below in Table 3. As opposed to our high priority requirements which form the basis of our design platform, these medium priority requirements are still important but do not contribute as directly to the outcomes of our product.

User Comfort

The first medium priority requirement we have is that users must be satisfied with the comfort of our device. Since our device will be used to aid in the rehabilitation process for our users, it is likely that there will be some inherent discomfort as they do the exercise to improve their range of motion and strength, so our necessary specification for this requirement is that our device does not increase the users pain rating on the 11 Numerical Rating Scale for pain [39]. We feel confident in the use of this scale for our purposes as it has been validated as reliable for rating pain in patients recovering from strokes [40].

Affordability

Our next requirement is that our final product be low-price. Our product is meant to be purchased and taken home by the patients of the clinic, and the price point given to us by a design ethnographer and confirmed by Dr. Shibu that patients would be able and willing to pay is 1000 rupees, which is equivalent to $12 [16], [23]. Therefore our specification for our product being low-price is that patients must be able to obtain our device for no more than $12.

User Preference

Our next requirement is that users prefer using our device over their existing at-home exercise methods. As explained to us by Dr. Shibu, many patients begin to lose interest in continuing their upper arm exercises once they return home, which stunts their recovery and can have serious long-term ramifications. He specifically highlighted that creating a product that patients would prefer to use over their current methods during their 30 minute exercise sessions at home would aid in their recovery, which directly led to this requirement [14]. In order to create a quantifiable specification for this requirement, we want at least 75% of users to state that they prefer using our device over their existing at-home methods when surveyed after using our device. We are confident in the basis of this specification as a way to quantify this requirement, but still plan to discuss the specification with Dr. Shibu before we decide that it is a complete specification.

Transportable

Another requirement we had was that our product needs to be able to be carried. If our product is intended to be used by the patients in the clinic, then purchased and taken home with them, they need to be able to transport it home with them. We learned from our design ethnographer and Dr. Shibu that many patients travel to and from the clinic on public buses, so the major concern with transporting the device will be that family members can carry the device on and off the bus [16], [23]. Based on that interview, we also expect patients to be traveling home with family members, so the burden of physically carrying our product will likely fall on them rather than the patients. In order to help quantify this specification, we are using the NIOSH (National Institute for Occupational Safety and Health) carrying index developed by the CDC, and are stipulating that our product score less than a 1 on that index [41].

Ease of Use

Since strokes affect mental cognition as well as the body, our next requirement is that users can easily understand how to use our product. Based on research into usability for other medical devices, our specification for this requirement is that 55% of users be able to achieve either complete success or success with a minor issue when using our device after being shown how to use it in the clinic [42], [43]. This specification is still marked as incomplete however as we still want to consult with more stakeholders to determine if this is a reasonable target.

Maintainable
Our next requirement is that our product be maintainable. Based on discussions with Dr. Shibu and our design ethnographer, our first specification for this requirement is that any parts needed to repair our product must be available locally to ensure that users are able to easily obtain any parts they may need [14], [16]. Since our product is meant to be taken home by patients, any repairs done will likely be completed by family members of the users without any specific specialized training tools, so our second specification for this requirement is that our product must be repairable with only a single tool. This specification is still marked as incomplete until we can determine more specifically what tool we can reasonably expect to be available.

Durable
Ideally, there would never be a need for repairs to be conducted on our product and with that in mind, our last requirement is that our product is durable. Taking into consideration the environmental and cultural factors in India where our product is intended to be used, we have heard from stakeholder interviews that there is no air conditioning in the rehabilitation center and the same is true for many of the patients at home [16], [23]. With that in mind our first specification for this requirement is that our product be able to withstand even the highest temperatures and humidity found in the region, which according to data from NOAA is 105°F and 100% humidity [44]. Based on information provided by Dr. Shibu that ideally patients would have three 30-minute exercise sessions a day for the duration of their recovery, which generally takes about a year, our second specification for this requirement is that our product be able to withstand three 30-minute uses a day for a year [14].

Table 3. Medium Priority Requirements

Requirement	Specifications
Able to satisfy user comfortability	Does not increase patient pain on Numerical Rating Pain Scale
Affordable for intended users	Less than $12 (1000 Rupee) for take-home component
Preferred by users over current methods	When surveyed after use, 75% of users prefer using the device over their existing at-home methods
Able to be carried	Scores less than 1 on the NIOSH index (National Institute for Occupational Safety and Health)
Easy to to be used	At least 55% of users able to achieve complete success or success with a minor issue
Able to be easily maintained at home	Replacement parts locally available

	Able to be repaired using a single tool
Able to withstand expected usage conditions	Withstand 100% humidity and 105°F Able to withstand 3 uses a day for a year Able to survive drops from a height of five feet

Concept Generation

To begin the concept generation process, each member of the team generated 40 concepts individually, using various methods. One of these methods was to utilize morphological matrices to generate ideas. Using this method, different components of the design were organized in rows, such as method of resistance, size, method of feedback, and motion tracking. Combining options from different rows allowed a variety of concepts to be generated. The use of morphological matrices allowed us to explore many different ideas. This method encouraged creativity by presenting various options for each element and ensured all relevant aspects of the design were considered during ideation.

We also applied design heuristics to create concepts or changes to existing ideas. We identified specific design challenges then applied a set of design heuristics to generate concepts. The design heuristics considered include user centricity, technological integration, adaptability, and modularity. Applying these design heuristics was relevant to our project, since our goal is to design a rehabilitation device, focusing on user needs, incorporating technology, and ensuring adaptability, and considering modularity for scalability are crucial design principles. The application of design heuristics helped the team generate concepts that addressed the unique problems associated with stroke rehabilitation.

We also utilized the method of functional decomposition to generate concepts. The design problem was broken down into three functional components that a full solution would have to encompass all of: motion tracking, resistance/exercise implementation, and engagement. We then generated concepts for each component and found ways to combine each component group into a full concept. This approach ensured that each aspect of the rehabilitation device is considered before integrating them into a full solution.

As a result of using a variety of methods to generate ideas, the concept generation phase resulted in two hundred individually created concepts. Some of these concepts were duplicate ideas generated by different team members, and after eliminating duplicate concepts we were left with about 150 ideas. Our design ideas explored a wide range of solutions that help rehabilitation. The concept space was fully explored using team collaboration which leveraged our different perspectives to generate ideas and conducting thorough benchmarking that explored the currently existing solutions, so that we had sufficient background information to ideate. Some ideas that were generated could be classified as "outlandish" solutions as they involved the use of things like animals or liquid tanks that patients could fully immerse themselves in. Concepts were also classified according to complexity. High complexity devices include a bionic arm, arm wrestling robot, hand exoskeleton, virtual reality, and a smart glove. Low complexity solutions include exercise bands, pulleys, dominos, grip trainers, and sorting cubes.

The main categories into which all of our concepts were grouped include wearable devices, gaming/interactive interfaces, therapy tools and equipment, simulators, virtual/digital guidance, art and craft activities, and resistance/strength training. The wearable devices category include the bionic arm, RFID sleeve, and smart glove. The gaming/interactive interfaces category included concepts such as a keyboard with games, motion tracking games, and a VR apparatus. Concepts under the therapy tools and equipment category include putty, weights, exercise bands, and a punching bag with magnetic gloves. Concepts that fall under the simulators category include motion capture within the clinic, driving simulator and guitar hero. Virtual/Digital Guidance concepts included an AI based app, gesture recognition, and a holographic therapist broadcast. Concepts in the art and craft activities category include clay forming, art with an instructor, and knitting. Resistance/Strength Training concepts include a modular exoskeleton, grip trainer and wall of sliders/wheels. These ideas were later filtered down during the selection stage to reach five developed concepts that met the requirements enough for consideration.

Exercise Mirror

One of these five concepts was an exercise mirror. With dimensions of approximately 56 inches by 23 inches, the mirror would be able to display a trainer who would assist the users in completing their exercises while allowing the user to see themself. The design consisted of an LED screen behind a one way mirror. The mirror would be equipped with sensors to track the user's movements allowing for the interactive display to provide visual feedback, showing progress and range of motion measurements. We ultimately did not decide to proceed with this design as it would be too expensive to produce and thus would not be able to be purchased by Poovanthi patients for 1000 rupees. Furthermore with the dimensions of 56 inches by 23 inches it would not be easily transportable from the clinic to a patient's home.

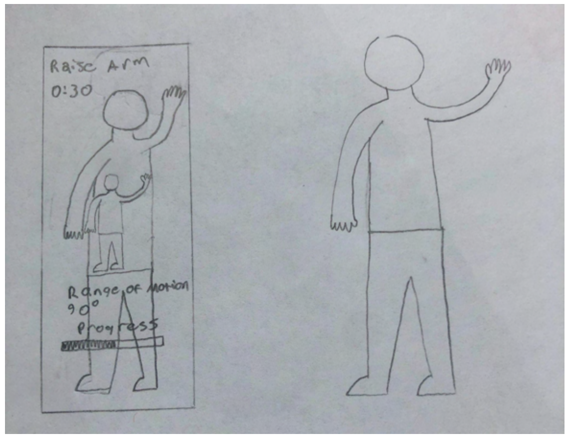


Figure 4. This figure shows a drawing of a user doing an exercise in front of the mirror. The exercise name is displayed on the top of the mirror along with a timer, and a trainer doing the exercise is projected in the middle of the mirror. Data on range of motion and progress is displayed on the bottom of the mirror.

Weighted Sleeve

Another concept was a weighted sleeve that a user could wear covering the shoulder, upper arm, forearm, and hand. This sleeve would be designed to enhance the range of motion in the affected arm by providing resistance, training natural and controlled movements, and aiding the individual in performing exercises to regain mobility. The sleeve would incorporate sewn pockets in which weights could be placed, allowing for adjustable weight based on an individual's rehabilitation progress. There would be pockets on the shoulder, the bicep, two pockets on the forearm, one pocket on the hand, and a pocket on each finger. The weights for the arm would be thin and rectangular, resembling a smartphone, while the weights for the fingers would be long, thin and rectangular in the shape of a finger. The weights would provide resistance during exercise, engage muscles in the affected arm, and enhance muscle strengthening to enable gradual recovery. The sleeve would be used during exercises and daily activities which would enable improved performance in daily tasks. The sleeve would be designed with material to provide a secure fit on the arm, preventing movement during use. While this concept does allow for strength and range of motion training of the entire upper limb and would potentially be able to be purchased at 1000 rupees or less, we did not select this concept because it is not able fulfill the requirements of measuring joint angles during exercise or helping improve prehensile grips.

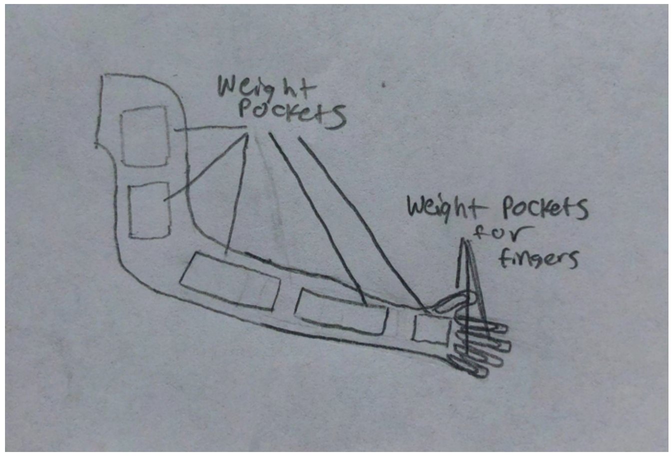


Figure 5. This figure shows a drawing of a wearable weighted sensor sleeve. Weight pockets are on the shoulder, bicep, forearm, hand, and fingers.

Sensor Sleeve

The next concept was a wearable sensor apparatus to connect wirelessly to a mobile app that consisted of seven sensors; one on each of the shoulder, bicep, forearm, hand, pointer finger, thumb and middle finger. The apparatus would incorporate accelerometers, gyroscopes and EMG sensors. The sensors would collect real time data on movements and muscle activity, as well as hand and finger positioning, The sensors on the fingers would capture data on finger movement and grip strength. This data would be transmitted wirelessly to a connected device via an application which could provide visual, auditory, or haptic feedback to guide the user to adjust their movements, ensuring they performed the exercises correctly. The app would have the ability to store the user's progress over time, providing information on range of motion, strength and dexterity gains. One reason this concept was ultimately not selected was because it would likely have been too complicated for patients to use. Consisting of multiple sensors and wires, users would need detailed instructions about how to set up, charge, and wear the apparatus. Without therapist help in an at home setting, we believe this would prove too difficult for 55% of users to achieve complete success or success with a minor issue using the device. Furthermore the device is not able to train strength by itself, additional weights would have to be used, and the accumulation of electrical components would likely have pushed the device way over 1000 rupees.

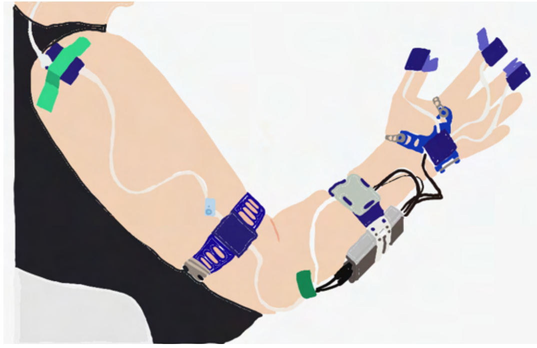


Figure 6. This figure shows a wearable sensor apparatus on the arm. There is one sensor on the shoulder, secured by tape that is connected by wire to a sensor near the elbow that is secured by a band. This elbow sensor is connected to the forearm sensor which is attached to the arm by a band which also secures a power brick. Wires from the forearm sensor and the power brick connect to the hand sensor, which connects by wire to the thumb, pointer finger, and middle finger sensors.

Motion Capture

Our next concept utilized camera tracking of the upper limbs with integration into an engaging game. Two cameras would be supported by tripods and placed to track the movements of the user's upper limbs. Computer vision algorithms would be employed to analyze the footage and detect key movements of the upper limb. These detected movements would be translated into a virtual representation on a screen so that the user could see their movements in a virtual environment. Users could engage with games designed to encourage specific movements by achieving gameplay objectives such as reaching targets, grabbing objects, or solving puzzles. A large reason that we did not proceed with this idea was that this solution would not be able to be sold at a price that could be afforded by Poovanthi Patients and additionally the device could only be used in the clinic not at a patient's home, due to its size, complexity and need for electricity. Furthermore, this device is not able to fulfill the requirement of helping users strengthen their motions.

Figure 7. This figure shows camera tracking of the upper limbs. Two cameras on tripods are positioned to the left and right of a screen that displays the virtual representation of their arms.

Interactive Slide Board

The final of the five concepts was an interactive slide board. The initial design for this concept was a baseboard that contained a 90 degree arc shaped slot. A thin rectangular board, known as the rotating arm, is attached to the slot at one end and a pivot at the other end. A handle would be attached to the rotating arm and could be slid along the length of the arm. The slide board was intended to train range of motion and strength by allowing users to position their upper limb on the rotating arm to move it through the range of the slot. The user could adjust the handle so that they position whichever joint they want to train (shoulder, elbow, or wrist) on the pivot. The user would then rotate their arm limb the arc keeping their joint at the pivot point. Five different handles to train each prehensile grip could be attached to the rotating arm with a pin. Variable weight would be able to be added to the opposite side of the board attaching to the point where the rotating arm intersects with the slot. Ultimately this concept was selected as the alpha design because it would be able to improve shoulder, wrist and elbow range of motion, train strength using variable weights,measure joint angles throughout the 90 degree slot, train the prehensile grips, and it would likely be able to be produced at a price that could be purchased by Poovanthi patients.

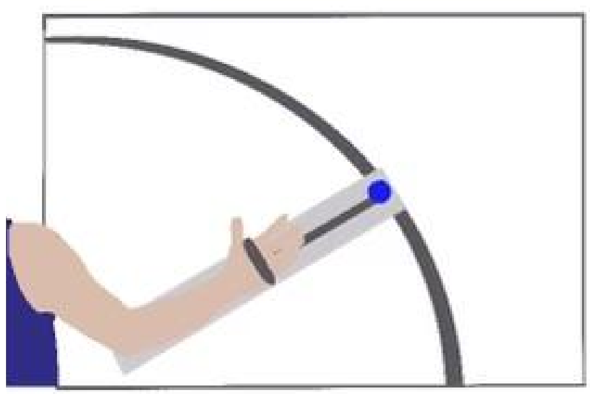


Figure 8. This figure shows a preliminary CAD design of the interactive slide board design. The arc is contained within a 2 x 1 ft rectangle which is supported by four cylindrical pegs on the 2 x 1 ft baseplate. The handle is cylindrical and a weight is attached to the end of the rotating arm.

Concept Selection Process

The individual concept generation phase resulted in two hundred concepts in total. We began by filtering through each person's designs to condense and eliminate duplicate ideas resulting in one-hundred fifty concepts. Next we filtered for feasibility considering our application at the

Poovanthi Institute, filtering out abstract ideas like painting, simplistic ideas like silly putty, and high tech complex concepts like full bionic exoskeletons, cutting the number of concepts to fifty. We then narrowed down the selection keeping only concepts that meet our requirements and specifications, finding that ideas like VR motion capture are far too expensive and out of the scope of our capabilities. We then identified the basic components of a potential solution. These were motion tracking, resistance or exercise implementation, and methods of engagement. Based on the components we identified, we were able to combine different elements in order to come up with twelve solutions that we felt broadly covered the range of components without feeling redundant. From these twelve concepts, we focused on feasibility and our perceived likelihood of that concept meeting our requirements and specifications in order to eliminate seven of those twelve concepts.This process is illustrated by Figure 8 below.

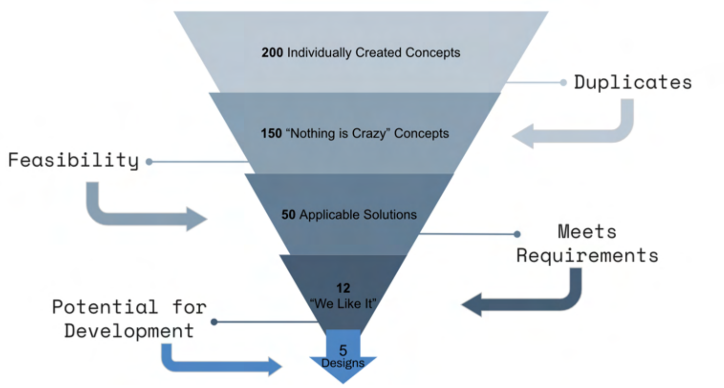


Figure 9. Filter pyramid shows the method of narrowing down concepts from initial two hundred to five selected designs.

These top five selected designs all meet the most important initial requirements of being engaging and functionally sound for exercising the whole arm. The exercise mirror can accommodate any exercise for the arm while remaining engaging as the patient can see both a trainer and themselves. The weighted sleeve can add weights to any part of the arm and is fun and easy to operate with. The sensor sleeve similarly can accommodate any movement and can connect to any game application for engagement. Camera tracking can be gamified as well as work for many compound movements like dancing. The slide board is designed for motion in all planes and for each muscle as well as having an incremental feedback component for attention. These five concepts each meet the requirements and specifications initially identified as a priority by Dr. Shibu and Lucy that put them above the rest of the primitive solutions, but they require a more critical in-depth filtering to reach a final selection.

After narrowing down the generated concepts to these five developed solutions, we needed a way to continue to narrow down the selection to one design to push forward. To do this we created a Pugh chart with updated requirements to weigh each of our priorities for each design such as cost, take home, strengthening, preferred to current methods, and whole arm exercise. With updated visions from Dr. Shibu, we decided to add the take home element and low cost as high priorities for the project goals, giving them a weight of 5 and 4 on the 1(lowest)-5(highest) priority scale. We kept the categories of strengthening and being preferred to current methods at a weight of 3 as they are not super high priority but still desired functions of the device. At a weight of 4, working the whole arm has a relatively high priority as a functioning device is imperative, the other factors can be supplemented later. A baseline of the current methods for in-home rehab in India of rubber bands and kneading dough was set to a level of 0, to which each of the designs were then compared for being better (+1) or worse (-1). The totals were then added up for comparison of the top five designs as shown below in Table 4.

Table 4 - Concept Selection Pugh Chart

Design	**Weight**	Rubber Bands and Dough (Baseline)	Exercise Mirror	Weighted Sleeve	Wearable Sensor Sleeve	Camera Tracking	Interactive Slide Board
Cost	5	0	-1	0	-1	-1	0
Can Take Home	4	0	-1	+1	0	-1	+1
Strengthening Element	3	0	-1	+1	+1	+1	+1
Preferred to Current Methods	3	0	+1	0	+1	+1	0
Works Full Arm and Hand	4	0	+1	0	+1	+1	+1
Total		**0**	**-5**	**8**	**5**	**1**	**11**

While the exercise mirror looked promising originally as a concept, the cost of the technology, difficulties to transport it, and the lack of a strengthening element hurt it during this round of analysis. The weighted sleeve is transportable and easily modified with weights, but it likely would not be preferred to current methods and it is difficult to load any movements in the horizontal plane since gravity is the only resistance. The sensor sleeve would likely be preferable to other methods and offer variability in strengthening and movements, but it is too complex and costly to be a valid solution for an affordable take-home device. Similarly to the sensor sleeve, the motion tracking has the same benefits and pitfalls with an additional problem in that it is not take-home, a camera setup would most likely be in-clinic only and difficult to transport. The interactive slide board however either matches or exceeds the baseline for each of the design requirements. Being a physical structure that aids motion in all planes when rotated, it can work the whole arm as well as strengthen by adding variable weight and is also able to be disassembled for easy transport. Based on the scores from the Pugh chart, we identified the slide board and the weighted sleeve as the most promising design concepts to move forward with. Between these two designs, we felt that the versatility of the slide board as opposed to the weighted sleeve as well as its higher score made it a better concept to move forward with.

At the outset of this project, our first solution concepts consisted of technologically advanced ideas like a bionic arm exoskeleton and VR, simple fine motor concepts like rubik's cubes and silly putty, and abstract engaging ideas like a petting zoo and painting. Some of the more technologically advanced ideas have remained in our top five concepts for their motion tracking abilities, but others have been filtered out. The design we have selected is related to one of the two hundred we created, but has not been fixated on in our minds since the beginning. By keeping an open mind, we have in turn captured the design space by incorporating the possibility for abstract ideas while keeping more plausible ideas open to variation and combining elements.

First Selected Concept - "Alpha" Design

The selected design, "the interactive slide board," is a simple, easy to use mechanical solution that should meet almost all of the specifications and requirements. The slide board consists of six main subsystems: base, pivot point, grip slider, different grips, angle markers, and a resistive element. The base is a raised 6" box that should prevent any added weights from scraping across whatever the device is resting on. The base will also allow for the device to stand up vertically, which will allow for more exercises to be accomplished. An initial CAD model of the design is shown in Figures 10-11 with the different subsystems and the main measurements. A more CAD model with more measurements can be found in Appendix C.

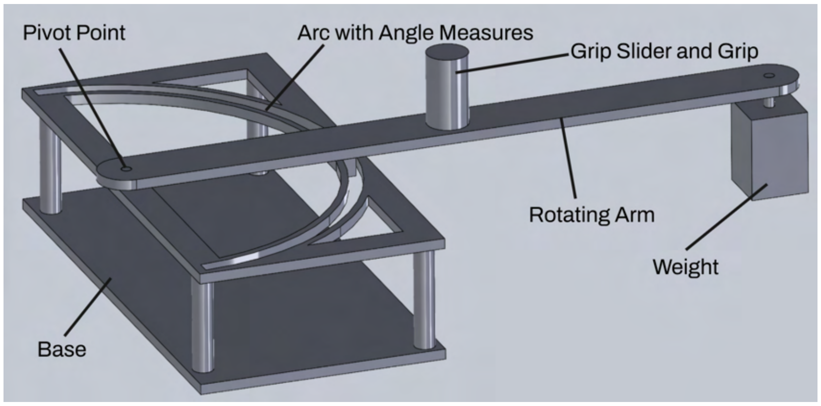


Figure 10. Interactive slide board has dynamic components of Rotating Arm and Grip Slider.

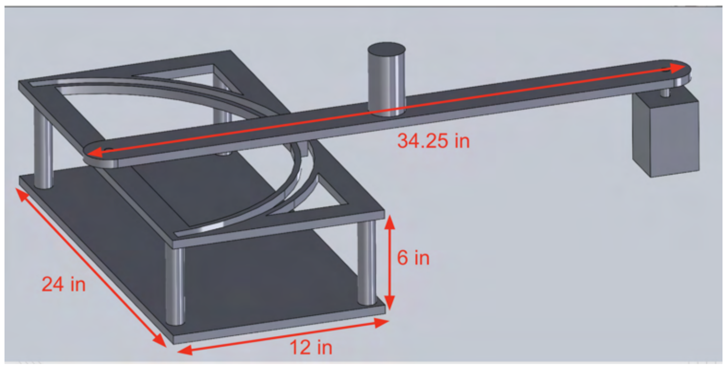
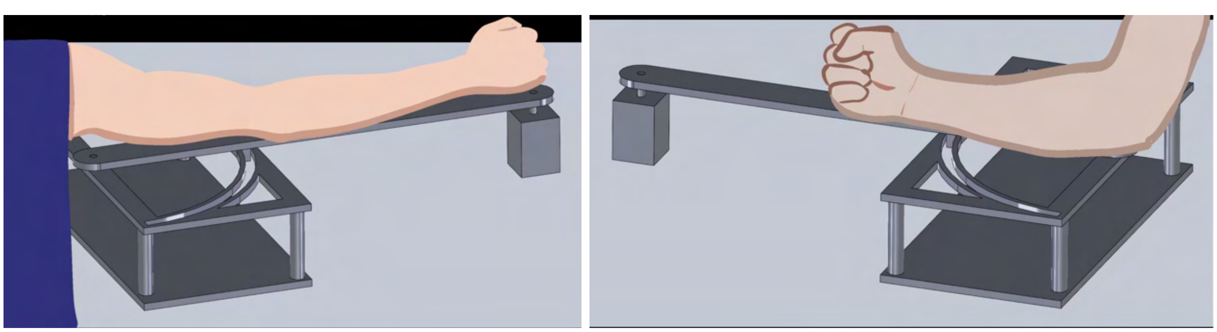


Figure 11. The Rotating Arm has a length of 34.25" to accommodate the 95th percentile arm length. Base has dimensions of 24" x 12" x 6" to aid in stability.

The pivot point is where users will rest whichever joint it is that they are working for a given exercise, whether that be the shoulder, elbow, or wrist. The pivot point will allow for 180° rotation to prevent the user from having to adjust the device to work different ranges of motion as most joints do not have a range of motion exceeding 180°. We are also currently considering adding a pad over the pivot point for comfort and extra stability for the user if they lean on it. Figures 12 and 13 show someone positioning their shoulder and their elbow above the pivot point for their exercises.



Figures 12 & 13. The human arm for reference shows how both horizontal oriented exercises operate for the shoulder (left) and elbow (right).

The grip slider slides along the rotating arm to allow the user to switch which joint they are focusing on. For example if they are working their shoulder, then the handle will be farther from the pivot point, whereas if they are working their wrist it will be closer to the pivot. The grip slider will have a clamp to prevent sliding in the radial direction once placed at the desired position on the rotating arm. The current idea for the rotating arm and slider is extruded aluminum similar to 80/20 with a slide as shown in Figures 14 and 15 below.

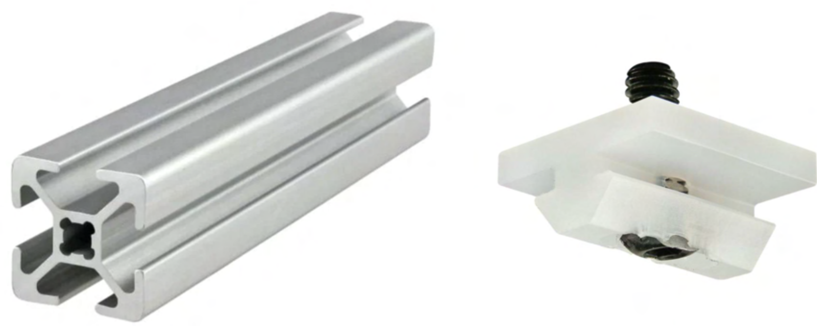


Figure 14 & 15. Current setup for the grip slider (right) in the rotating arm (left).

The grip positioner will have five interchangeable grip attachments to allow the user to use all six prehensile grips discussed in the introduction section as shown in Figure 16 on the next page. These attachments will fit into the grip slider holder and a pull pin will hold it in place. The pull pin should allow for attachments to be interchanged with just one hand.

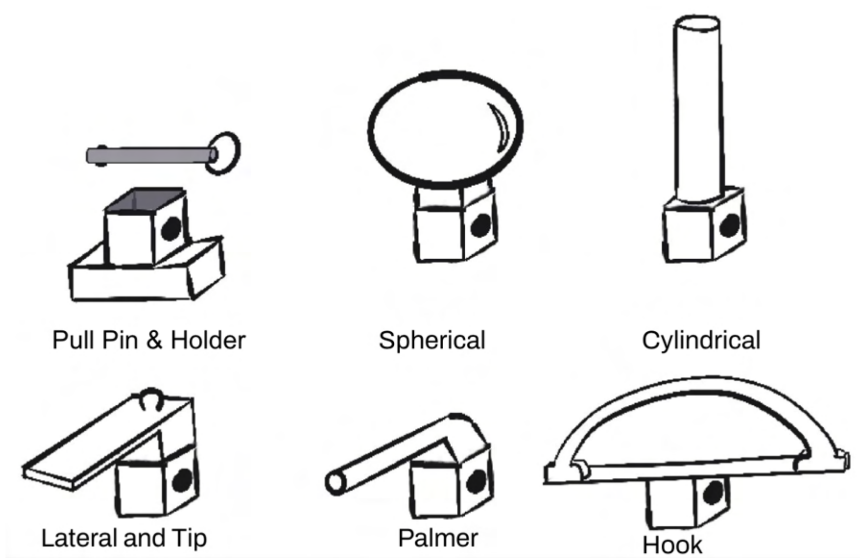


Figure 16. Six prehensile grips modify the hand position and muscles activated during exercises.

The rotating arm will be attached to the base at the pivot point and also along an arc having a radius of one foot. Along the arc there will be markings for different angle measurements or levels to allow for the user to see their progress. An adjustable hard stop can be used in conjunction with these markings to allow users to constrain their motions to specific angle ranges to prevent them from going too far and possibly injuring themselves.

There will be a resistive element to allow for the user to progressively increase the strength of their muscles. This will be implemented with a weight that can be attached to the end of the rotating arm. The weights will range from 0-15 pounds to work each joint's movement capabilities. While vertical, the device will rely on gravity to create the resistance from the weight. When it is in the horizontal position, adding weight will increase the friction between the rotating arm and the arc which will make it more difficult to move laterally. While the exact forces will not be the same between horizontal and vertical uses of the device, the constant increments will remain, allowing users to vary the resistance of the device.

This concept, along with the wearable sensor sleeve and the camera tracker were presented to Dr Shibu at a stakeholder meeting. He highlighted the mechanical slide board as the best suited for him and his patient’s needs as it is very simple to understand, low cost, adjustable, and allows for all joint movements to be worked in the upper extremity. We came to the same conclusion using our weighing scales as discussed in the Concept Selection Process section. Some aspects that need to be more fleshed out include different mounting solutions to make the vertical layout less likely to topple over, increasing the pivot point location’s adjustability in the vertical layout to prevent someone from having to squat or stand for different joint exercises, and possible changing the resistive element to something constant so it does not change in relation to its position with gravity. We believe that this project will be able to be completed within the scope of the ME 450 class and we hope to have a working prototype by the end of the semester.

Alpha Design Engineering Analysis

Tipping Analysis

Given the shape of the design with overhanging weights, a major safety concern is the tipping of the device. If the support structure is not sufficient, the device is at risk of falling over when weighted horizontally, or when oriented vertically. To combat this, we have conducted generalized moment calculations to assess tipping in the horizontal orientation as well as how much force can be applied horizontally when in the vertical orientation, shown in Figure 17 below.

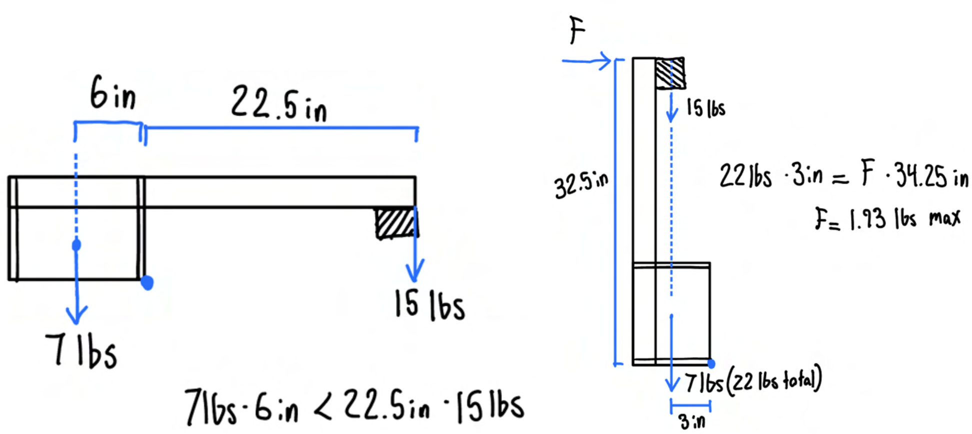


Figure 17. When oriented horizontally (left) the 15lb weight creates a moment much greater than the weight of the base and will tip if not adjusted. The vertical orientation (right) shows the maximum force F that can be applied at the top of the arm before it falls, equating moments of the weight and the applied force.

With these diagrams, we conclude that when oriented horizontally and fully loaded with the fifteen pounds, the device will tip if the base stays at its current dimensions. This means we must either modify the dimensions of the base, or add in a stability component such as weighing it down or adding in a clamping feature. When vertically oriented, the maximum amount of force applied when fully extended is around two pounds. Once again, we may need to add in a stabilizing component or make the base heavier or wider to avoid tipping. As the design progresses and we modify the base design, the moment will continue to be calculated with a safety factor, to ensure our design is stable.

Horizontal Force Friction Analysis

The requirement states that the resistance element needs to provide a range of force from 0-66.7 N which is equivalent to at least 15 pounds of force. For the device to be able to do this for all of the movements it is designed for, the friction force in the horizontal position must be equivalent to 15 pounds. Figure 18 below shows the normal force (F_2) on the arc created by the maximum weight on the end of the arm. Using this result and modeling the interaction of the arc with the rotating arm as a point mass, the coefficient of friction between the two surfaces has to be greater than or equal 0.375.

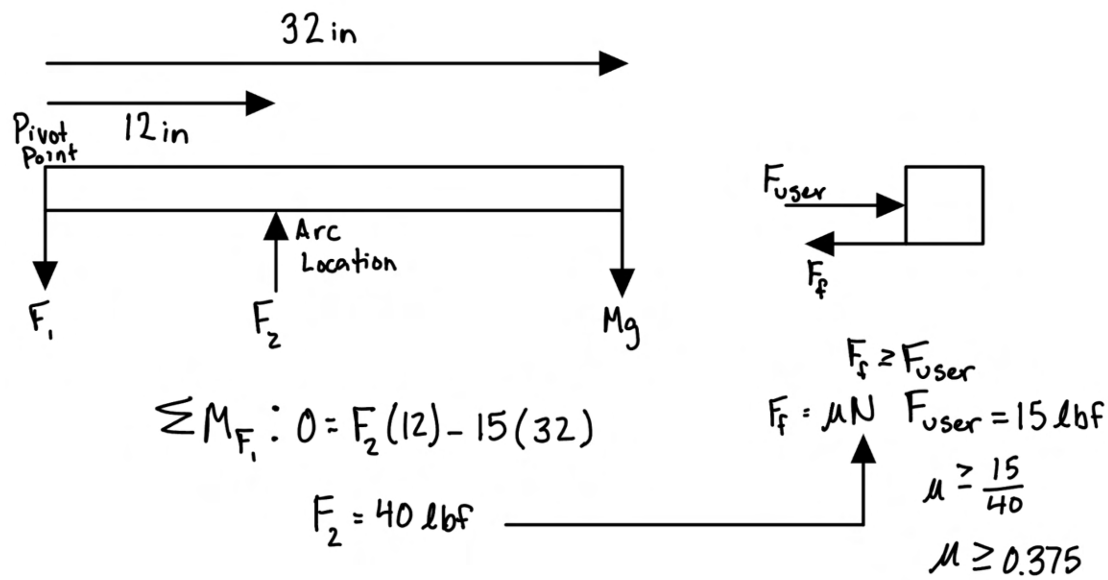


Figure 18. With the weight at the end, the calculated force at the arc location of forty pounds allows for a friction force derivation of at least .375 given that the user should be applying fifteen pounds of force.

However, after further investigation the model used above was over simplified as the assumption that the interaction between the arc and the rotating arm can be modeled as a point mass does not take into account that when the user has their arm at the far end of the rotating arm (near the added weight) it creates a moment arm from the point of friction. As described later in the Problem Analysis and Iteration section, we are looking into a new resistive element that does not require any added weight to create the friction.

Material Selection Analysis

An important factor to both the stability, weight, price, and overall function of the device is material selection. Using Granta, a material selection library and software offered by CAEN, we are able to assess different materials and create filters based on the figures we have for some of the material properties we have investigated so far. The four properties evaluated were yield strength, price, density, and Young's modulus. Figure 19 below shows four graphs that each contain the material groups within Granta based on a specific property on a logarithmic scale.

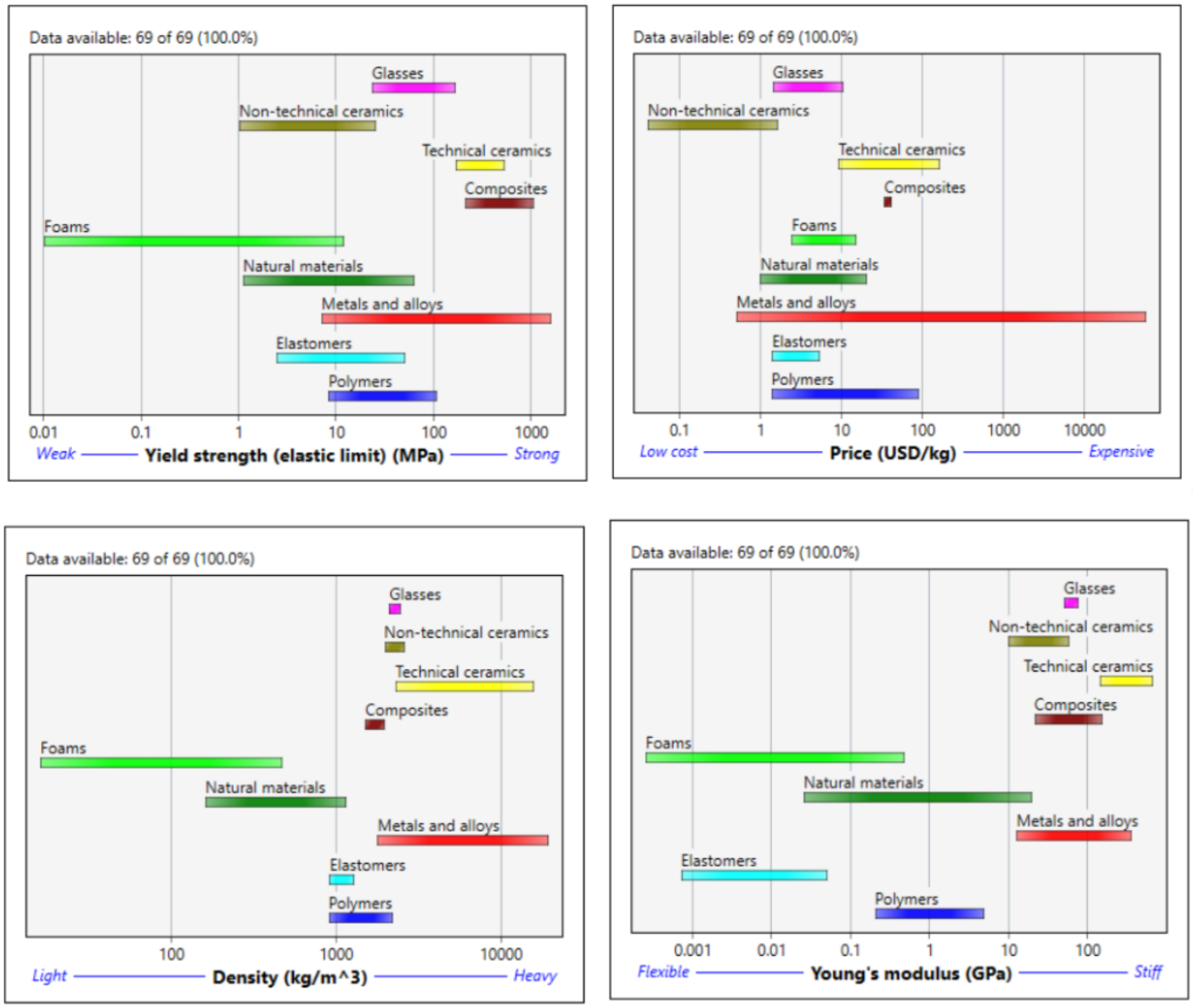


Figure 19. Shown are graphs from the ANSYS Granta material selection library. There are general trends for the materials that can be observed such as foams and natural materials being on the lower end for most criteria, elastomers and polymers being in the middle to higher end, and ceramics and metals making up most of the higher ranges for each criteria.

These graphs helped us gain a sense of what kinds of materials would suit each material property and to what degree. Yield strength was investigated so that we could pick a material that would be durable as per our requirement and survive accidental bumps, falls, and drops. Cost was evaluated so that we could understand what materials will help us keep the cost of our solution low to help fulfill our price requirement. Density was looked at to determine which materials could be used to keep the solution lightweight, so that it may be easy to transport as per another requirement. Young's modulus was also investigated to know approximately what materials will be durable enough to withstand everyday bending forces, especially since the rotating arm is not fully supported and could experience a deflection over the 20 inches from where it is supported to where it holds the weight. We were able to define minimum and maximum values for these material properties, along with a value for the melting point. We chose to not evaluate materials with this property in a graph because it is only a minimum specification, so it was just taken into account when seeing what materials pass all of the other criteria. In Figure 20 below, the criteria values are shown as well as the material groups that fulfill all of them.

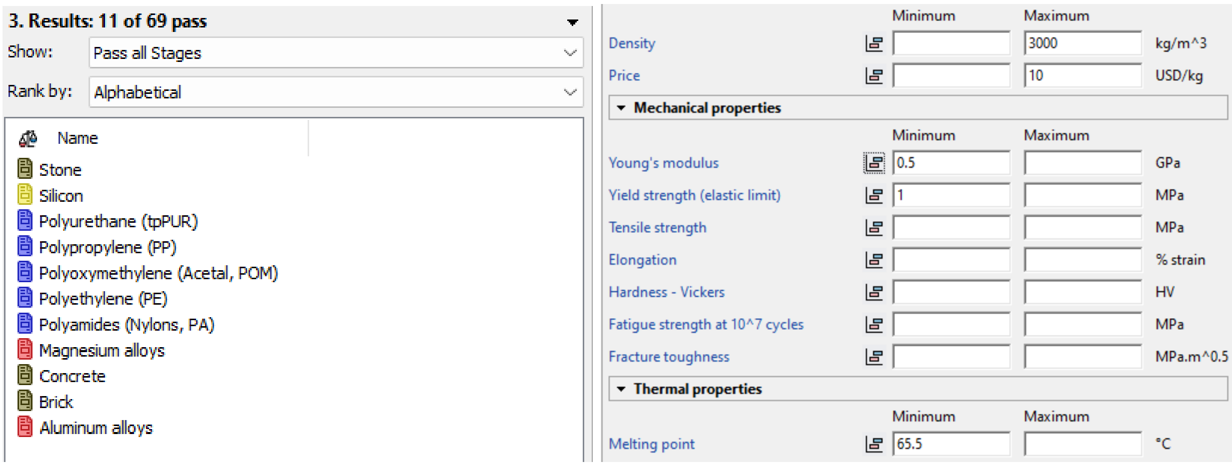


Figure 20. Shown are the criteria values used to narrow down the material groups within Granta, as well as the 11 out of 69 evaluated materials that passed all criteria. The criteria was maximum density of 3000 kg/m^3, maximum price of 10 USD/kg, minimum Young's modulus of 0.5 GPa, minimum yield strength of 1 MPa, and minimum melting point of 65.5 °C

From our results of this analysis, we are left with possible materials that would work for our solution. The values selected were very broad to allow us to personally evaluate materials and not set a constraint that would eliminate too many possibilities so that we are able to explore tradeoffs. A quick look at the list will show some that seem unfit to be used in our project, such as stone, concrete, or brick, as they are difficult to form and machine. We did expect aluminum to be a viable material in our brainstorming since it has many different alloys and forms, but we can see magnesium may also be good. The rest are silicon and polymers which we will be able to explore the tradeoffs and benefits in our future work.

Problem Analysis and Iteration

Considering our project and the requirements and specifications that we have developed to this point, most of the fields and fundamental engineering aspects that will come into play for us are within our domain of mechanical engineering. Looking more closely at our requirements and specifications, especially through the lens of our selected concept, we can see that while some will be fairly easy to analyze, some will be a bit more difficult for us.

For instance, our first few requirements have specifications focused on allowing full ranges of motion for different body parts. While we may not have much background in kinesiology, we can easily determine whether these full ranges of motion are achievable by our device. Looking at our selected concept, we can see fairly quickly that by allowing 180° of motion, we should be able to meet those requirements. Similarly the next requirement of providing ways to work on all of the functional prehensile grips is something we can easily look at theoretically and see that our selected concept should be able to meet that requirement with the different handle attachments. We also can easily meet the next requirement by adding the angle markers onto our device and hard stops to help constrain that motion as desired.

As we move onto our next requirement, the manner of verifying and testing our design's ability to meet the specifications becomes more complex. Using techniques from the field of solid mechanics and dynamics, we can use a variety of calculations to verify that our selected concept should be able to provide the loads we desire, and once we begin to prototype we can empirically measure the loads our device is able to produce to further validate our design. The next requirement of adjustability and accommodation is also similar, as we can use relevant data as well as engineering calculations and models in order to see how our device should be able to accommodate different users, and once we prototype we can easily take measurements to verify these findings.

As opposed to those already discussed, our remaining requirements and specifications begin to move outside of our normal domains of expertise. Whereas many of the above requirements were fairly easy for us to consider and analyze throughout our design process, many of these remaining requirements are more difficult for us to consider. With that in mind, we have a wide array of stakeholders and resources that we have been in contact with throughout our project, and we plan to continue taking advantage of the guidance they have been able to provide us as we move forward and further analyze our selected concept through the lens of our requirements and specifications.

Adjustable Height Issue

In terms of more technical design issues we are considering moving forward, the first one is how to adjust the height of the device. If someone is seated and the device is set on the table in the horizontal plane, we need to design for an adjustable height so that the pivot point meets the desired joint for varying sizes of patients. This is also the case for when it is rotated to be used in the vertical plane. In combating this possible design problem, we are exploring adding adjustable legs similar to those of an easy-up tent for variable height of the box itself. Another solution path is to hang the device from a door with hooks of adjustable length similar to a hanging mirror.

Resistive Element Issue

A second design issue we are considering is the resistive element for strengthening. Currently, our design includes physical weights on the end of the sliding bar that can have the potential for a safety hazard when falling vertically as well as contribute to a higher likelihood of tipping. To make the design safer and more stable, we are moving in the direction of eliminating the weights entirely as the resistive element and adding brakes and resistance to the track itself. This can be done through adding a variable friction element to the track such as those similar to stationary bike brakes.

Tipping Issue
Continuing on the possibility of tipping and stability as the design progresses, a major issue we must monitor is the moment calculation and tipping since the bar overhangs the support. To account for this, we are designing for a large rectangular base to stand on both when horizontal and vertical as well as the possibility for additional orthogonal support legs. This requires the continuation of moment calculations as the design changes in actual dimensions as well as weight distribution changes due to material.

Material Selection Moving Forward
Moving forward in working on prototyping and material selection, we are imagining the slide bar to be either a lightweight metal like aluminum, or plastic. The structure can have a bit of weight to it to ensure stability while remaining cheap so something like wood or aluminum would suffice. To figure out for sure what materials we want to select, we plan to do further material analysis on the strength of the structure to avoid failure when loaded.

Problem Domain Analysis and Reflection

Now that we have identified the project background, context, and have identified requirements and specifications that apply for all possible solutions, we can discuss the limitations at our current stage in the design process. Given the state of our knowledge of the project, we know about the desired goals for the project and what the design must accomplish in terms of enhancing the at-home rehabilitation process, but we lack an in-depth analysis of a selected design concept. At this stage of the project we have just scratched the surface of basic calculations that prove feasibility of our design. After filtering through many design concepts and landing on one of a more structural nature, we will need to use extra resources such as material from ME 211 and ME 240 to continue complex statics and dynamics calculations in modifying our design. We will also need to use practices adopted from ME 350 to assess the bearings, joints, and linkage aspect of our selected concept. Each of these resources will be necessary in solidifying the feasibility of our design moving forward.

A major anticipated challenge at this early stage of development is designing a concept that applies to both inpatient and outpatient rehabilitation. Dr. Shibu has requested that we explore the option of creating a device that can be used for inpatient rehabilitation that can tend to multiple patients at a time, and he has also expressed heavy interest in developing a take home component for patients to continue their rehabilitation outside of the institute [18]. The challenge then becomes figuring out how to either design a device for both, incorporate a detachable take home device from the inpatient one, or to choose one to focus on. Another anticipated challenge is creating a device that enhances rehabilitation for all parts of the arm. It is easy to focus on one joint at a time but creating one unit that can work all parts of the arm could quickly complicate a design. Finally, a challenge we are setting at a high priority to tackle is figuring out how to keep the patients actively involved in rehab. As discussed in the background and benchmarking sections, current rehabilitation leaves patients bored and not wanting to keep exercising with the old equipment [16]. Since rehabilitation in general is a non-pleasant activity, we are anticipating difficulty in creating a solution that can change that, which is why we are prioritizing it moving into the design phase. These three challenges of finding a preferably low cost inpatient device with a take home solution, enhancing rehabilitation for the whole arm, and keeping the device engaging have been challenges for other rehabilitation advancements as well and have been left as gaps in the industry. A device that captures all three is our intended solution. Knowing these are our priorities, the adoption of our selected concept being a cheap structural device that works the whole arm and can be easily taken home, the new anticipated challenge becomes making the design preferred over current methods. The challenge becomes how can we take our design and either add components to make it enjoyable, or make the device so compatible with daily functioning that it does not impair or interrupt other daily activities.

In solving these anticipated challenges, we plan to continue to meet with Dr. Shibu, Lucy, and current occupational therapists at the university to inquire further into current methods and how to design our device to hit the gaps in the industry. This means asking Dr. Shibu what is most important for the institute in terms of enhancing current rehabilitation versus how to accommodate the take home aspect for outpatient treatment. Also reaching out to occupational therapists, those who know current practices to find out what works for whole arm treatment, as well as what aspects of current treatment keep patients engaged. More specifically, a way to inquire about making our selected concept preferred over current methods can mean asking Dr. Shibu or Lucy about the possibilities of adding a more expensive component for in clinic such as a potentiometer at the pivot point. Another idea could be to ask about the daily activities that patients may be integrating with their rehabilitation at home to add integrative components. If the patients are not impaired by using the device and they can multitask while using it, the point of engagement is solved as there is no longer a disincentive to use it.

A possible deliverable to our design would be a prototype of the bar and sliding track system. Although it seems difficult to predict the feasibility for the remaining half semester as analysis and design changes are still ongoing. A concrete manageable deliverable is a detailed CAD design with all analysis and dimensions and components finalized. In working towards finalizing the design, the anticipated design specific challenges are detailed above in Problem Analysis and Iteration on page 30 and 31.

Build Design - “Beta” Design

We built a rough prototype of our design to test features such as the resistive elements, wheels to prevent friction, vertical adjustability methods, and range of motion. This prototype was made with wood primarily with some aluminum attachments to prioritize speed and critical changes that would be shown by usability testing. Parts for this prototype are shown in the bill of materials below in Table 5 followed by a picture of the build in Figure 21.

Table 5 - Beta Build Design Bill of Materials

Description	Qty.	Manufacturer	Part #
2' 2x2 board	1	In House	
2'x1'x0.5" plywood	2	In House	
4"x32"x0.5" boards	1	In House	
3"x3"x1.5" block of wood	1	In House	
3.142'x0.5"x1/16" aluminum sheet	1	In House	
2"x12"x1/16" aluminum sheet	2	In House	
2"x2"x1/4" aluminum angle bracket	1	In House	
2" long 1/4" dowel pin	2	In House	
5" long 1/4" dowel pin	1	In House	
1/4-20 wood screws	13	In House	
1/4-20 wood screws	3	In House	
1/4-20 bolt	1	In House	
1/4-20 nut	1	In House	
felt pad	1	Everbilt	49860
suction cup	1	QEP	75000
door hooks	2	Haute Decor	AWH402

Figure 21. The entire Beta build is shown in the horizontal position just as a patient would place it before doing horizontal arm exercises.

Wheel Attachment

The wheel attachment is made from a 1.5”x1.5”x4” wooden block with two closet wheels attached for the purpose of preventing friction between the arm and the arc while rotating. The wheels are drilled into the wood at an angle so the metal angle brackets do not interfere with the arc and have a 0.5” gap between them to fit the height of the arc. The metal screws that secure the brackets allow for there to be a tight tolerance for the width of the arc, so that the wheels can constrain the arm from deflecting significantly. The wheel block attachment is shown in Figure 22 below.

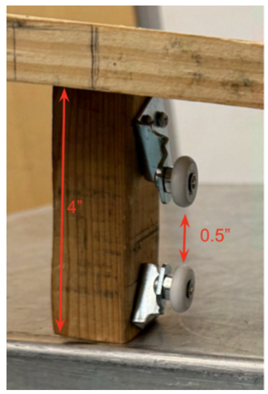


Figure 22. The wheels shown are attached to the wooden block without being placed on the track. Even with this tight tolerance, the wheels are able to slide onto the arc easily.

Resistive Element

The resistive element is made from a strip of felt attached to a wood block, which is supported by an aluminum angle bracket to the underside of the rotating arm. The wood block had two holes drilled into it for guiding dowel pins. These dowel pins line up with the angle bracket and keep the felt lined up with the side of the arc. The angle bracket has a tapped hole for a bolt which is used to adjust how much force the brake puts on the arc. The angle bracket has three holes to attach to the arm where it is screwed into. Figure 23 below shows the resistive element.

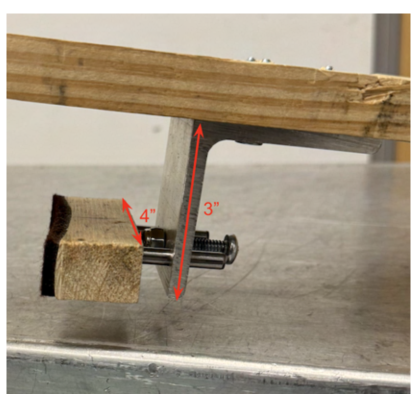


Figure 23. The resistive element is shown attached to the underside of the arm, and without the arc. The wood block has a curve cut on the end to increase contact area on the arc.

Arm

The arm consists of a 4"x32"x0.5" board with a hole on the end for a pivot point and attachments such as a spacer, resistive component, and wheels. The wheel block is attached 9” from the end to allow space for the wheels to get on the track. The resistive element is 13” from the end to allow for the brake to have enough room not to touch the arc and provide zero friction when set to the easiest setting but also close enough to have a good compressive force once fully tightened. On the pivot point, a 3”x3”x1.75” block is secured with two wood screws to allow space for the upper wheel to align with the top of the arc. This is attached using two wood screws. Finally a 1⁄4" hole is drilled at the pivot point to create a spot for the long dowel pin that will be added later Figure 24 below shows the arm assembly.

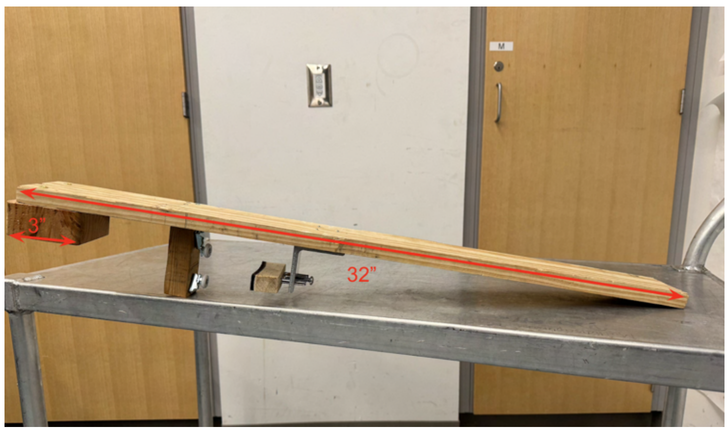


Figure 24. The entire arm assembly is shown. In this build, the arm is attached to the spacer, the wood block with wheels, and the resistive element.

Base

The base is a 1’x2’x0.5” piece of plywood with a slot at each end and a circle cut out in the middle. The slots are 9”x1” cutouts to allow for over-door hooks to fit into the base to hold up the device in the vertical position. The circle cutout in the middle is a 4” cutout that a suction cup can be placed in which is also meant to support the device in the vertical position. All cutouts from the board were made using a drill to create a starting point and using a jigsaw to cut out the rest of the shape. The base is shown in Figure 25 below.

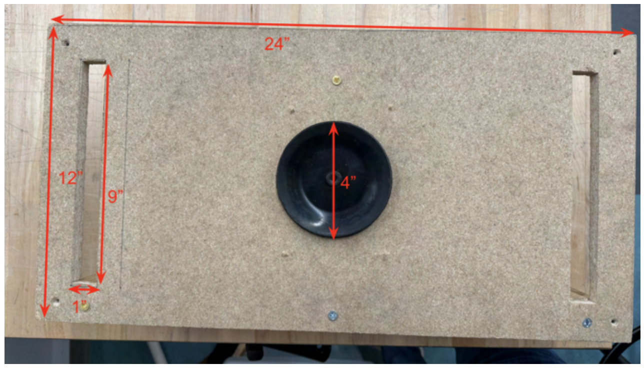


Figure 25. The underside of the beta build is shown, with the suction cup interface and rectangular cutouts on either side to support changing orientation to perform right arm and left arm exercises.

Arc

The arc of the device was also made from a 1'x2'x0.5" piece of plywood that is fashioned into a D shape to allow for a full 180° of rotation for whichever joint is being exercised by the user. The outer radius is 11" and the inner diameter is 8.5". The outside of the arc has a 1/16" aluminum sheet to simulate the final design friction when tested. The arc is shown in Figure 26 below.

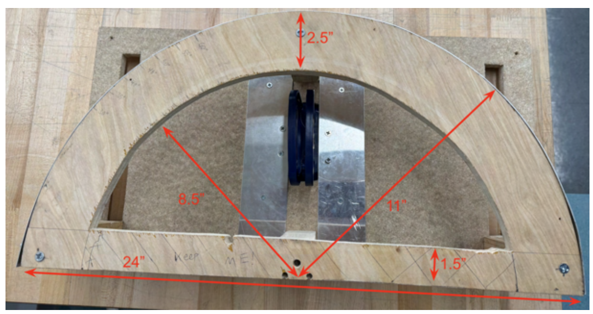


Figure 26. The top view of the arc is shown, with fasteners fixing it to the support posts, the aluminum surface on the outside, and the dowel pin hole for the arm assembly in the middle.

Assembly

The arc is connected to the base with three support legs made from 5"x2"x2" pieces of wood. There is also a support with the same dimensions for a pivot point. The full assembly is shown in Figure 27 below.

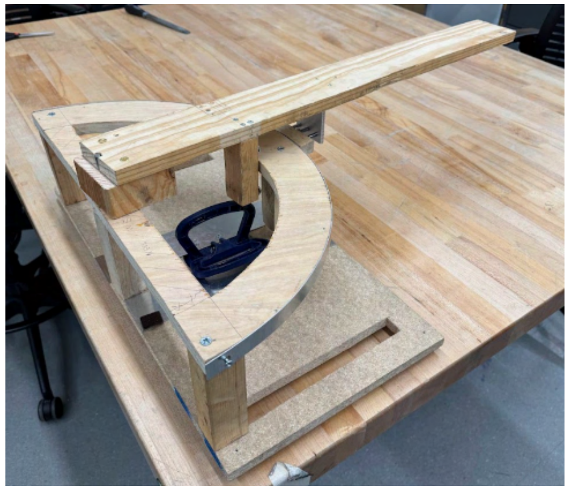


Figure 27. The entire assembled arm board is finished when the arm is placed and connected to the arc.

The slide board is meant to be used in both the horizontal and vertical planes to allow users to work a wide variety of exercises as shown in Figure 28 below.

Figure 28. The left orientation shows how a user can perform shoulder exercises in the vertical plane and the right orientation shows how a user would perform an elbow in the horizontal plane.

The arm was mounted to the pivot point with a dowel pin to constrain the arm. The arm rests on the D shaped arc using an attachment with wheels to allow for the arm to rotate around the arc a full 180°. This 180° rotation is designed to allow for a full range of motion for most joints as referred to in the specifications and requirements with the straight part of the D providing extra support to the pivot point and acting as a hard stop. The wheels prevent the arm from moving off of the arc to prevent the user from pulling the arm off of the device if they accidentally pull away from the machine in the vertical position and they also lower the required force to rotate the arm for patients that have less strength.

The adjustable brake element allows the user to change the amount of force that they need to exert to move the arm. This is meant to allow the user to increase resistance and build strength throughout their rehabilitation at home. The initial design used a weight as the resistive force, but was changed to a friction force to allow for a constant load in any orientation. The wheels and the resistive element are two parts of the design that must have smaller tolerances as they must be close enough to the arc to do their specific functions.

The suction cup and overdoor hooks were added to allow for adjustability in the vertical position for height differences and for the height difference between their shoulder and elbow.

Beta Design Engineering Analysis

In pursuing a final design that is sound and executes our desired requirements, we identified multiple design worries that needed to be addressed and then ranked them in order of importance to complete the necessary testing. We identified the high priority concerns worthy of testing to be that the device must be able to; be oriented vertically with adjustability in height, to have stability in both directions, to slide with minimal resistance, and to have variable resistance. We chose these as high priorities over things like durability, longevity, and transportability as the functional ability of the device is more important than secondary factors that can be modified later. To test these we looked towards design solutions that addressed each concern. For vertical adjustability we tested door hooks, stability we tested a suction cup, minimal resistance we tested roller wheels, and for variable resistance and strength training we tested multiple brake pad materials.

Door Hook Analysis
The initial design worry with the alpha design is that the device needs to be able to be oriented vertically without tipping or moving. The free standing alpha design without any clamps or attachments was very likely to tip if placed on its smaller edge (vertically) and presented a risk for the user. To solve this problem we introduced the idea of having door hooks that go over the door like a hanging mirror to hold the device. They would be adjustable in height to accommodate many users and it would hook into slots in the base of the device's frame.

In testing the validity of the door hook design, we chose the mode of empirical testing with adjustable door hooks we found at Home Depot. We believe empirical testing is the appropriate testing method and level of detail in that it will allow us to visually see how stable the device is. This gives us the ability to make a simple pass/fail judgment call on its validity without needing the specificity of numerical force values. We are assuming that the user sets up the device and hooks properly, that they place their joint at the correct location, and that they apply forces in the typical direction for their exercises. To execute the testing we needed to manufacture 1" by 9" slots in the base for the hooks to hook through. We then hung the device from a door and applied ample force to the arm for the vertical shoulder exercise simulation as shown below. Figure 29 is repeated below for visualization.

Figure 29. The beta build in the vertical position is supported by door hooks and the suction cup.

The results of this testing yielded a failure for the design concept in that when we applied any substantial perpendicular force the whole system shifted in a four bar linkage fashion. While the door hooks provided ample ability to hold the device and adjust vertically, it simply could not provide enough rigidity to execute the exercise when presented with perpendicular forces. We acknowledge the limitations of the simplistic empirical testing and how factors like length and rigidity of the hooks themselves affect the deformation, but the tests showed that even with stronger hooks the device would still need further stability measures as the movement was so drastic. We are very confident in the validity of the empirical testing as it clearly presented us with the issues with the design concept itself. The key takeaway from this testing is that our door hook method of supporting the device in the vertical alignment is not feasible, and as such we are no longer planning to rely on this method in future iterations of our design.

Suction Cup Analysis

Similarly to the door hook analysis, the initial design concern with the alpha design was the ability to adjust the height of the device in the vertical direction as well as stability in the horizontal orientation. To combat this problem we introduced the concept of a heavy duty suction cup that would allow the user to attach the device to the wall at whatever height they needed. It would also add stability in attaching it to whatever surface it rests upon when used horizontally.

In testing the validity of the suction cup design change, we iterated on the alpha design by adding a hole in the base for the suction cup to go in. We then chose to once again use empirical testing as the analysis method as we felt calculations on the suction forces were too complex of an analysis to simply determine if the concept could work, so we elected instead to empirically test it as pass/fail. The assumptions we made were that the user in a typical home in India would most likely be attaching this to a wood door or drywall. Therefore we tested the suction cup by attaching the prototype to a wood door and applying a force in the vertical direction measured by a force gauge, to see how much weight it could support in shear. The force that it took to move the prototype in the vertical direction was the maximum force that the device could support. We also applied rotational forces by tightening the resistive brake pad to simulate the device in action and to test torsion strength of the suction. A force gauge was used to determine how much force was exerted on the arc by measuring the amount of force needed to rotate the slider arm when the brake pad was tightened. We then repeated this process for drywall and metal surfaces. We acknowledge the limitations that the suction cup we used in testing may not be identical to ones found easily in India and that the testing conditions like humidity differences and surface quality between the testing environment and India could also have an affect on the suction cups ability to stick. That being said, we feel that for the purposes of quickly checking the feasibility of this design change our manner of testing was adequate.

From the applied force tests, the results initially showed that the suction cup could withstand substantial vertical forces on both wood, drywall, and metal. But after continued testing, the suction cup began to wear and the surface collected dust to the point where it could no longer hold the device while it was in use. The device would slide down the wall with minimal force. Additionally, when rotational forces were applied the suction cup also slid and rotated on both the wood and drywall. From these findings we are confident in concluding that the suction cup design solution does not require further testing as we have found it to not be feasible or worth pursuing further. Moving forward we will move away from the suction cup design as it did not pass simple empirical testing for validity.

Wheel Analysis

Another design worry we have is related to the alpha design initially consisting of a slot that the arm would slide along. The worry is that this would introduce too much friction in the unloaded state in addition to being complex to manufacture. To solve this we decided to change the design from an open slot to simply having the arm roll on wheels to reduce friction and simplify the arc. Once again we chose to test the concept of roller wheels empirically over mathematically as we felt it would be a much simpler and more convincing method of determining the validity of the design change.

In testing the validity of the wheels, we attached a piece of wood to the bottom of the arm to support two drawer wheels we purchased from Home Depot. We then put the arm back onto the device, having replaced the slotted arc with a solid one. We then tested how easily the arm rolled around the arc by pushing it along as it would be used. While this prototype and manner of testing was not the highest fidelity, we felt that this form of testing was adequate to determine the feasibility of using roller wheels to reduce the effects of friction on the motion of the arm. The arm could be rotated by a force of 0.1 lbs, measured by the force gauge.

The results of the wheel testing showed us that the arm moves with ease as it rolls, with close to zero amount of force being applied. This means that for patients who have lost most of their strength, they will be able to start their rehabilitation at an easy level requiring next to no force.

From these findings we are confident that the idea of using wheels for the arm to roll on is a valid approach. The design change proved beneficial and will be implemented in the final design iteration. To continue to develop the concept, additional testing will be necessary such as measuring the amount of force it takes to move it in the unloaded state as well as testing to see if the new attachment style onto the final design arm affects its motion at all.

Brake Pad Analysis

A major problem and design worry with the initial design is that the device had hanging weights as the variable resistive element that could potentially cause harm from falling as well as creating a greater inclination for the device to tip. To solve this problem we got rid of the hanging weights and replaced them with a brake pad design similar to that of an exercise bike as the resistive element. This consisted of a wood brake pad with a chosen material on the end that one could tighten or loosen to reach the desired resistance. This "chosen material" is what is being tested through our brake pad analysis. We needed to find a material that would provide enough resistance when fully tightened to introduce at least 15 pounds of force, yet retain the ability to slide on aluminum with varying amounts of force applied. A piece of rubber would not suffice as it would have no variability, once it touches it would stick too much.

To test this we chose empirical testing with our prototype as it would provide direct feedback for how the materials would interact versus calculations that may not correctly represent the interactions. We first constructed the brake apparatus shown in Figure 30 below and then attached the different pad materials on the end. We tested a rubbery material and a felt material we got from Home Depot. The friction coefficient of felt on aluminum is 0.34. We were unable to find the exact friction coefficient for rubber on aluminum thus we estimated it to be the same as rubber on stainless steel, 0.64. With each material we tested how much the very first contact impacted the resistance, the maximum resistance, as well as how much variation in resistance the materials could create throughout the tightening. For our testing scenario, we are assuming that the user has the means to tighten the brake fully. We acknowledge that the contact of the aluminum on the prototype will be different because the final design may have a slightly different finish but we are accepting the general results of how the materials interact.

Figure 30. Brake pad assembly applies friction to the outer arc aluminum surface, easily tightened by the bolt and slides along the dowel pins.

The results of the brake pad analysis yielded a successful material selection of the felt pad. The rubbery material had a strong maximum force but failed because there was not enough variability in resistance. Once the material contacted the aluminum it stuck too much even at a loose setting. The felt pad on the other hand slid easily on first contact, had the ability to tighten gradually, and reached a maximum tightness of no sliding at all. This means that the felt pad could be tightened as much as needed. We are confident in these findings and have concluded that no further testing is needed as we are choosing to move forward with the felt pad in our final design.

Exercise Analysis

In the introduction we showed some of the common movements and exercises that are performed with the upper limb as shown in Figure 1 on page 4. Of these 12 movements, we can do 8 of the 12 movements fully, however aspects of each movement can be exercised.

Analysis Results Summary

We completed four major analyses empirically with our alpha design prototype of testing door hooks, a suction cup, wheels, and brake pads. While the door hooks supported our requirements of vertical adjustment, it could not withstand the horizontal forces and shifted during use which violated the need for stability during exercise. This caused us to abandon the idea as the tests failed to demonstrate the validity of the design concept. The suction cup was also abandoned as we found that it could not provide enough stability, especially when resisting sliding and rotating forces. Even when using both the door hooks and suction cup in conjunction the desired stability was not achieved. The wheels however proved to be a successful design change as they allowed for seemingly frictionless motion. They worked during testing, leading us to move forward with the concept on to the final design. Finally, the brake pad material selection led us to move forward with felt as it provided good variable resistance. We ultimately tested four design worries and their associated design change solutions, passing two and failing two.

Final Design - “Gamma” Design

The final design will resemble our build design but it will differ in several ways. The final slide board consists of a baseplate which supports four cylindrical posts, three of those posts are 5.5” and attached to an arc, while the other post supports a 29’’ long slotted aluminum bar which serves as the slider arm. Attached to the bottom of this bar, on the inside of the arc is an L bracket which supports two wheels that contact the top and bottom of the arc. Another L bracket attached to the bottom of the bar, outside of the arc, connects to a brake mechanism by dowel pins. A 3D printed slider mechanism inserts into the slotted aluminum and is secured by a bolt which can be tightened by hand; five different 3D printed handle attachments can be inserted into the slider and secured by a pin. The user utilizes the device by adjusting the slider so that they can position either their wrist, elbow, or shoulder at the pivot point while gripping the handle, then securing the slider by tightening the bolt which is screwed into the slider until it contacts the bottom of the arm’s slot. The user would then adjust a bolt/nut mechanism to either increase or decrease the friction between the brake and the arc thus modifying the resistance the user would face in moving the slider arm. The user would then grip the handle and perform the desired exercise over a certain range of motion. The slider arm is able to move along the arc because it is attached to a 7.25’’ cylindrical post by a shoulder bolt creating a pivot point as well as the fact that the slider arm is supported by two wheels that allow it to move with little friction. The wheels were chosen after our engineering analysis determined that wheels would reduce the amount of friction the slider arm experienced relative to the alpha design in which a protrusion of the slider arm slid along a slotted arc. The brake mechanism is able to function because a felt material was chosen to cover the brake’s curved surface after engineering analysis. The felt material allows the slider arm to still be able to move even when the friction is high between the arc and the brake. All components of the final design are shown in an assembly below in Figure 31.

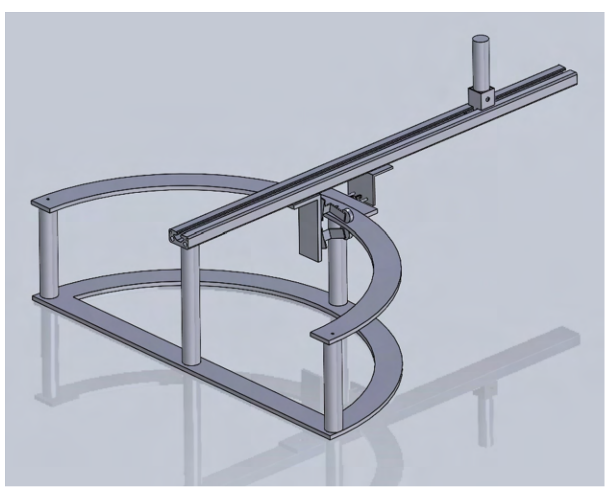


Figure 31. This figure shows the assembly CAD of the final design. The cylindrical handle is inserted into the slider.

The final slide board will consist of an aluminum base plate in the shape of a D with a thickness of 0.25", an outer radius of 12” and an inner radius of 10.5”. There are four 0.15” tapped through holes along the frame that will attach to four posts using 10-24 screws. This base plate design is different from the 2’ x 1’ baseplate of the build design. After testing the build design in the vertical position, by moving the slider arm throughout the 180 degree arc, it was determined that the device would often become un-suctioned from the surface it was attached to and the hooks did a poor job of constraining the device’s motion vertically. Thus it was decided that we would abandon our device’s ability to be oriented in the vertical plane, therefore, the baseplate would no longer need to contain a circular cutout for a suction cup nor two rectangular cutouts for door hooks. Thus the baseplate could be designed as a D shape as opposed to a rectangular shape, this would reduce the mass of the base plate relative to the build design. The dimensions of the baseplate are shown in Figure 32 below.

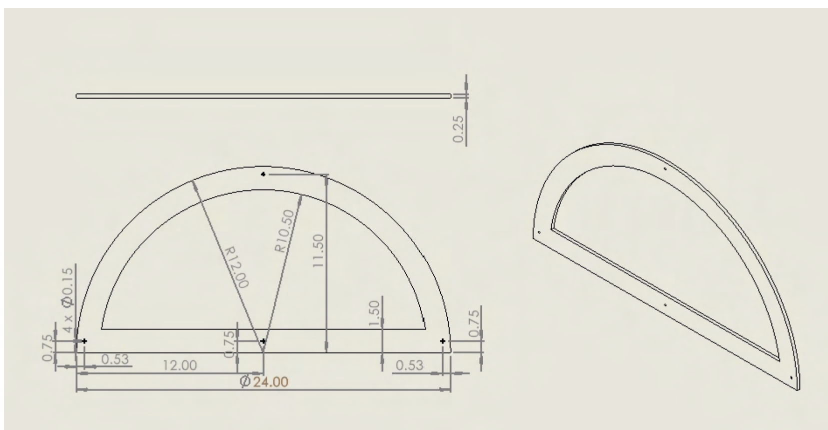


Figure 32. This figure shows the engineering drawing of the base plate.

There are three 5.5” tall, 1” diameter cylindrical aluminum posts which attach to the base plate on the bottom and the arc at the top. The posts will have 0.15” diameter tapped holes drilled ⅜” deep at the center of the top and bottom faces to attach the posts to the baseplate and arc. These posts differ from the 1.5’’ by 1.5’’ rectangular posts in the build design as they are cylindrical with a diameter of 1". This change was made to decrease the overall mass of the device, not use wooden materials to keep in line with the environmental conditions of India, and be easier to clean. The height of the posts in the final design was changed to 5.5” from 5” in the build design to maintain the distance from bottom of base plate to the top of the arc at 6”. The dimensions of the support posts are shown below in Figure 33.

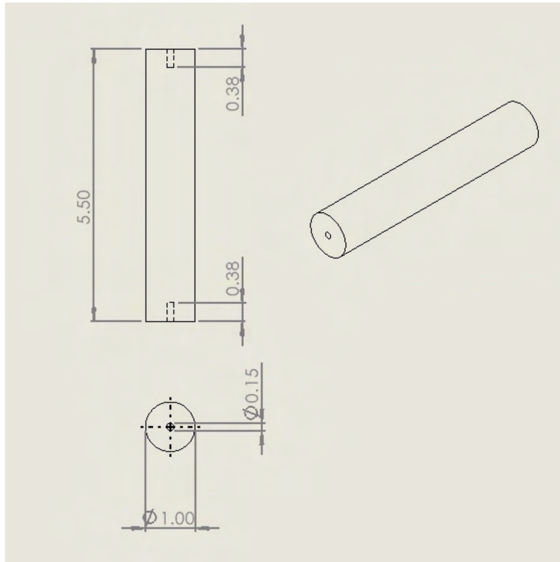


Figure 33. This figure shows the engineering drawing of the three posts that attach the baseplate to the arc.

The arc is aluminum in the shape of a C with an outer diameter of 12”, an inner diameter of 10.5”, and a thickness of 0.25”. The arc has three 0.15” holes that will be tapped to attach three posts with 10-24 screws. The arc in the final design differs from the arc in the build design slightly, as the thickness of the build design arc is 0.5” while the final design arc is 0.25” thick. This change was made to decrease the overall mass of the device and to maximize the ease of manufacturability. The dimensions of the arc are shown in Figure 34 below.

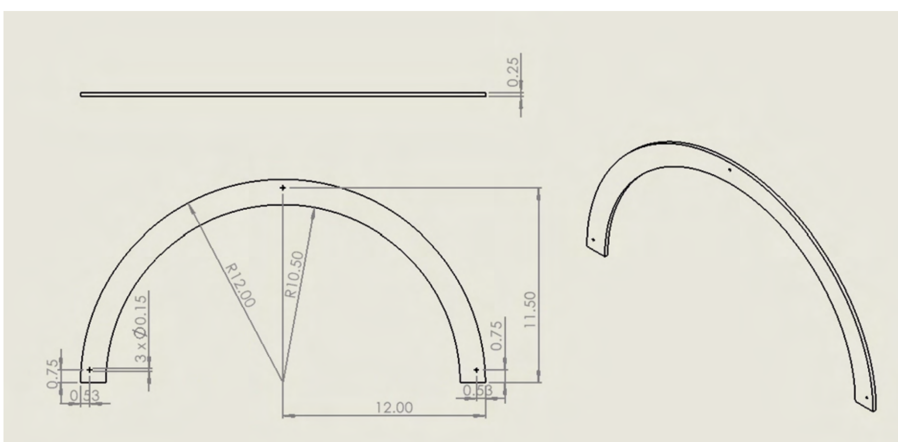


Figure 34. This figure shows the engineering drawing of the arc and its dimensions.

There is a 7.25” tall, 1” diameter cylindrical aluminum post which supports the slider arm at its top face and connects to the base plate on its bottom face. On both the top and bottom faces of this post, there is a 0.15", ⅜” deep tapped hole. A 10-24 screw attaches this post to the baseplate and a shoulder bolt attaches the post to the slider arm. The height of this post changed from 5” in the build design to 7.25” in the final design, as the arc in the build design was in the shape of a D, meaning this post extended from the base plate to the arc, which was a distance of 5”. The distance of 7.25” was selected to maintain a gap of 1.25” between the bottom of the slider arm and the top of the arc. The dimensions of the long post are shown below in Figure 35.

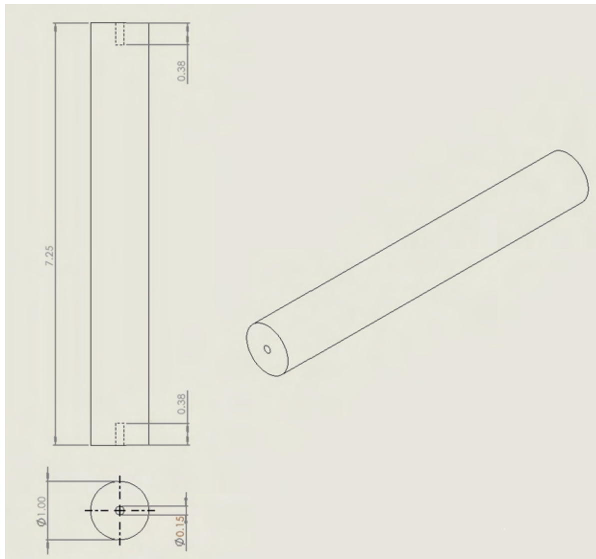


Figure 35. This figure shows the engineering drawing of the long post that attaches to the baseplate and supports the slider arm.

A 29” long 80/20 slotted aluminum bar with a 1.5” x 0.75” cross section will serve as the slider arm. There will be a 10-24 tapped through hole in the slider arm that will line up with the 10-24 tapped hole in the 7.25” post. This slider arm is completely different from the slider arm in the build design, as the build design slider arm was always meant to be a temporary substitute. The length of the slider arm was reduced in the final design to 29” from 32” in the build design. The dimensions of the slider arm are shown below in Figure 36.

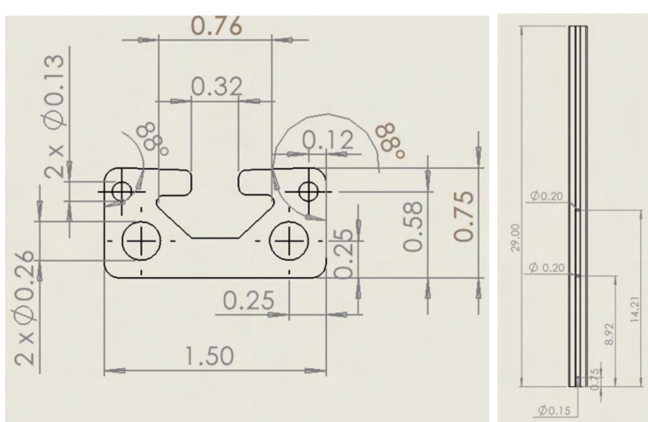


Figure 36. This figure shows the engineering drawings of the front profile and the top profile of the slider arm.

An aluminum angle bracket with a 4” length, a 2" length and a 1.5" width is attached to the bottom of the slider arm by a 10-24 screw at a distance of 8.92" from the end of the slider arm along the 2" length. Two wheels are attached to the 4" length of the angle bracket angled diagonally, contacting both the top and the bottom of the arc. There is a 0.201" through hole at the center of the 2" length which lines up with the 0.201” diameter through hole 8.92" along the slider arm allowing a 10-24 screw to insert attaching the L bracket to the slider arm. In the build design the mechanism the wheels attached to was a 1.5” x 1.5” x 4” tall wood block, this design was changed for the final version of the device to be an aluminum L bracket in order to reduce the mass of the device, make manufacturing easier, and be easier to clean. The assembly and the engineering drawing for this L bracket is shown in Figure 37 below.

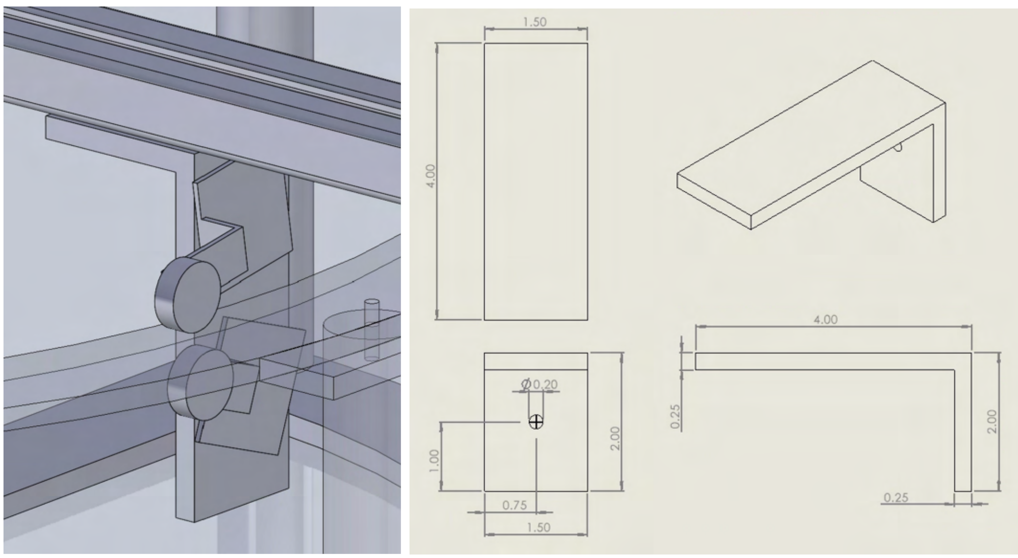


Figure 37. This figure shows the final design CAD assembly focusing on the angle bracket attachment to the slider arm and the wheels attached to the angle bracket and the engineering drawing of the angle bracket in the CAD. The point of attachment for the wheels will need to be determined so they are not shown on this drawing.

Another aluminum L bracket with lengths of 1.5" and 1.88" and a width of 2" is attached to the bottom of the slider arm at a distance of 14.21" along the length of the slider arm. A 0.201” diameter through hole at the center of the 1.5" length of the L bracket lines up with a 0.201” diameter through hole at 14.21" along the slider arm creating a hole in which a 10-24 screw is able to be inserted attaching the L bracket and slider arm. Along the 1.88” length, there are two 1/8” diameter holes. The center hole is a tapped hole of diameter 0.15”. These dimensions are shown below in Figure 38.

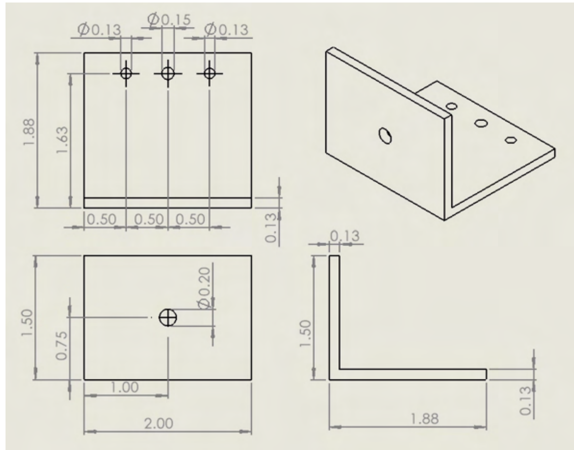


Figure 38. This figure shows the engineering drawing of the L bracket that attaches the slider arm to the brake mechanism.

The brake mechanism is an aluminum block with a 4" length, 1’’ width, 0.25’’ thickness and a curved surface of radius 12", it connects to the L bracket by two ⅛’’ dowel pins. The flat side of the brake has two ⅛’’ diameter, ⅜’’ deep holes in which the dowel pins insert. The dimensions of the brake are shown below in Figure 39.

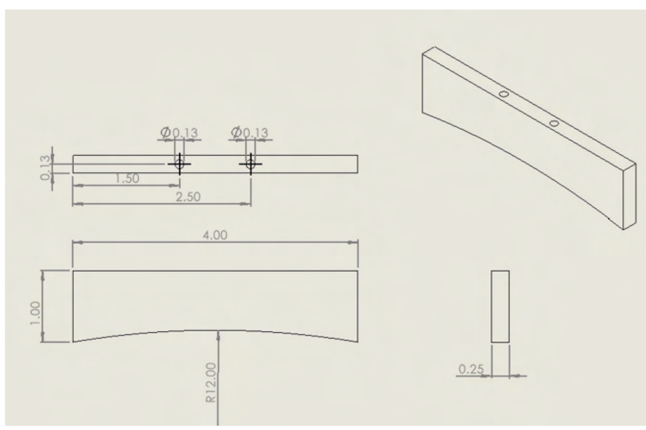


Figure 39. This figure shows the engineering drawing of the brake mechanism.

The L bracket is 0.64" offset from the brake. The curved surface of the brake is covered in a layer of felt, its distance to the arc can be adjusted using a bolt. The bolt inserts into a threaded hole in the L bracket, a nut attached to the end of the bolt contacts the brake. When the bolt is tightened, the nut will exert more force on the brake bringing it closer in contact with the arc exerting more normal force on the arc, creating higher friction. When the bolt is loosened, the nut will exert less force on the brake, resulting in the brake exerting less normal force on the arc, creating lower friction. The assembly of the L bracket to the arm and the brake is shown below in Figure 40 below.

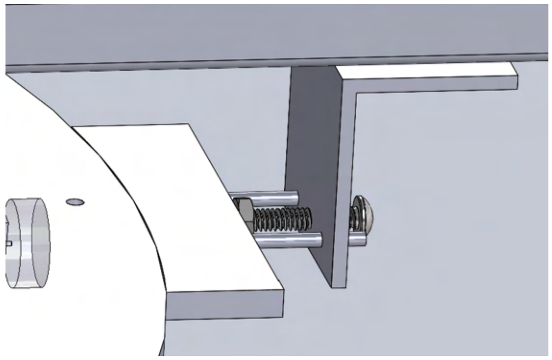


Figure 40. This figure shows the final design CAD assembly focusing on the angle bracket attached to the slider arm and the brake attached to the angle bracket by dowel pins as well as the bolt/nut mechanism which allows for the adjustment of resistance.

A 3D printed slider mechanism inserts into the slot of the slider arm. The slider will be 3D printed because this method of fabrication is the easiest for the complex design of the part. The slider consists of a 1" by 1" by 1" cube with 0.05" thick walls. There are two 0.25" holes on opposite sides of the cube in which a pin can insert to secure the handle into the slider when inserted. An inverted T shaped profile extends from the bottom of this cube which fits into the 80/20 slider arm slot. A portion of this inverted T shaped profile extends, in the center of the extended section, there is a 10-24 threaded hole in which a bolt can be screwed into until it hits the bottom of the slot, securing the slider into a fixed position. The dimensions of the slider are shown below in Figure 41.

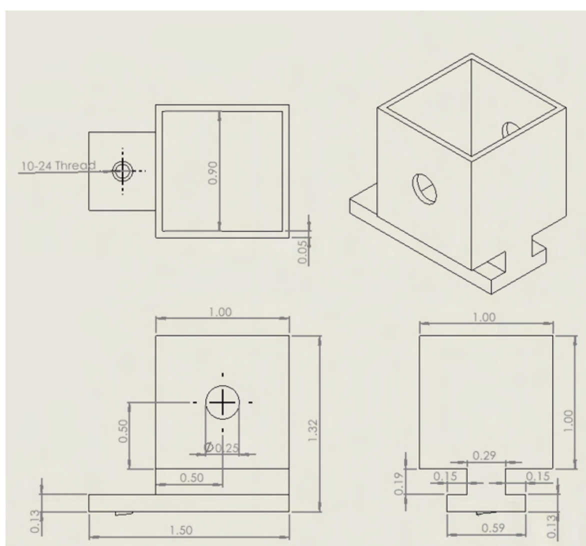
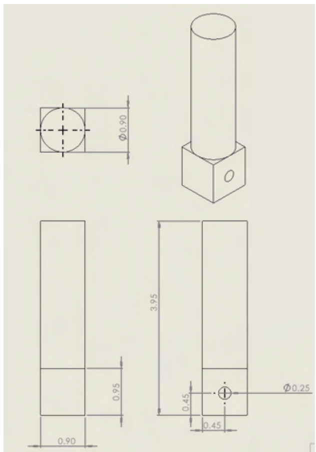
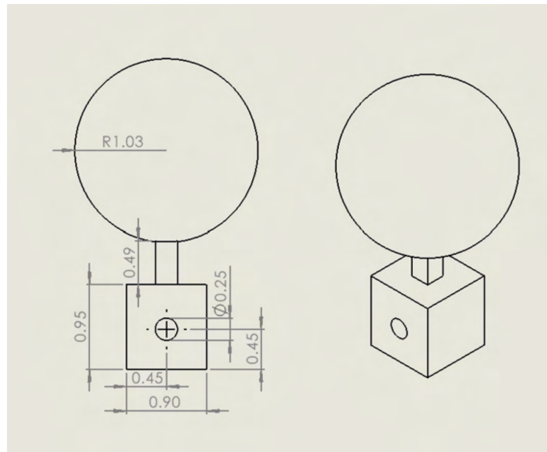


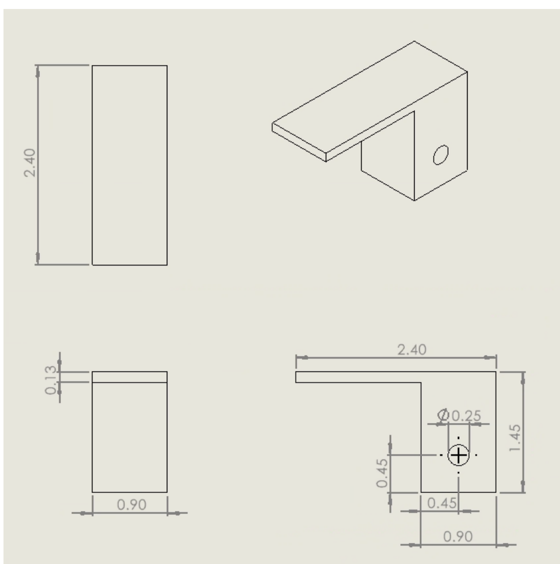
Figure 41. This figure shows the engineering drawing of the slider mechanism.

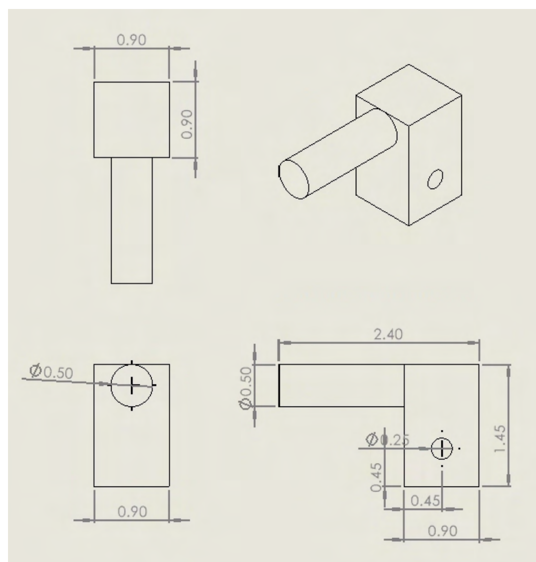
We will 3D print five different handles that train five different prehensile grips. Each handle will be able to be inserted into the slider. The handles consist of a 0.9" x 0.9" x 0.95" base which fits into the hollow cube of the slider. There is a 0.25" diameter hole which cuts through the entire base, this hole lines up with the holes on the slider. A pin can be inserted into this hole to secure the handle to the slider. Each handle differs in what structure is on top of the base, handles include cylindrical, spherical, lateral/tip, palmar, and hook. The dimensions of each handle insert are shown below in Figures 42-46.





Figures 42 and 43. These figures show the engineering drawings of the cylindrical and spherical handles.





Figures 44 and 45. These figures show the engineering drawings of the lateral/tip handle and the palmar handle.

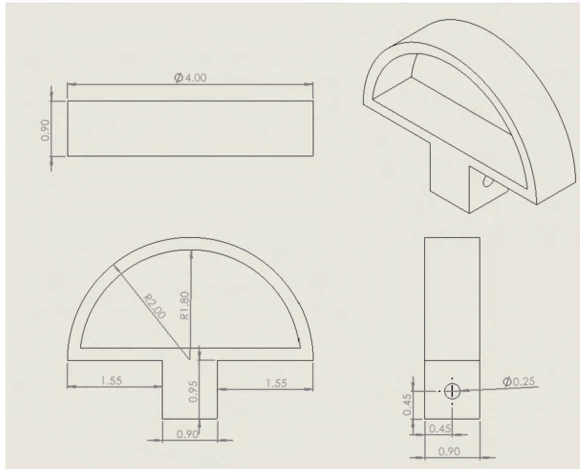


Figure 46. This figure shows the engineering drawing of the hook handle.

Verification and Validation Approach

Of our total of fifteen requirements, the methods of verification we used for each of their specifications can be divided into three main categories; verified by design, verified trivially, and verified through more involved methods. The first category, specifications verified by design are specifications that are more simple and can clearly be seen to be met simply by virtue of the design of our device. The specifications that can be verified trivially are those that only require simple analysis or testing to quickly determine whether the specification is met or not. For the remaining specifications, more in-depth or complex tests and analysis are required to verify the specifications. All of our requirements and specifications have been divided between these three categories or assigned to more than one of these categories, as can be seen below in Table 6.

Table 6. Manner of Verification for Specifications

Requirement	Specification	Verification Type
Able to help users improve shoulder range of motion	Allows for total range of motion (0-180° abduction, 0-60° extension, 0-180° flexion, adduction 180-0°, external rotation 0-90°, internal rotation 0-70°, horizontal abduction 0-45, horizontal adduction 0-135)	By Design Trivially
Able to help users improve elbow range of motion	Allows for total range of motion (flexion: 0-135°, extension: 135-0°)	By Design Trivially
Able to help users improve wrist range of motion	Allows for total range of motion (Supination: 0-90°, Pronation: 0-90°, Wrist flexion: 0-80°, Wrist extension: 0-70°, Radial deviation:	By Design Trivially

	0-20°, Ulnar deviation: 0-30°)	
Able to help users improve their functional prehensile grips	Capable to grip: cylindrical, tip, hook, palmar, spherical and lateral	By Design Trivially
Able to measure joint angles for users during exercises	Able to delineate angle measures between 0°-180° with increments of 5°	Trivially
Able to help users strengthen their motions	Allows for variable loads from 0-15 lbs	Complex
Able to accommodate users	Allows for radius of rotation for patients up to 95th percentile: 2.31 to 28.94 inches Able to accommodate users scoring at least a 3- on the MMT scale	By Design Trivially
Able to be cleaned and is safe	Meets criteria for CDSCO Approval to be Class A: Is not intended to 1) come into contact with injured skin, 2) channel or store substances, or 3) modify compositions of substances.	By Design
Able to satisfy user comfortability	Does not increase patient pain on Numerical Rating Pain Scale	Complex
Affordable for intended users	Less than $12 (1000 Rupee) for take-home component	By Design Complex
Preferred by users over current methods	When surveyed after use, 75% of users prefer using the device over their existing at-home methods	Complex
Able to be carried	Scores less than 1 on the NIOSH index (National Institute for Occupational Safety and Health)	Complex
Easy to to be used	At least 55% of users able to achieve complete success or success with a minor issue	Complex
Able to be easily maintained at home	Replacement parts locally available Able to be repaired using a single tool	By Design
Able to withstand expected	Withstand 100% humidity and 105°F	

usage conditions	Able to withstand 3 uses a day for a year	Complex

Range of Motion Requirements
Our first three requirements center upon allowing users their full ranges of motion at the three main joints our device focuses on: the wrist, the elbow, and the shoulder. The specifications for each of these three requirements are simply that our device must allow for users to reach the normal ranges of motion for those joints, as measured through the angle of that joint. During our design process we were able to at least initially verify through design by ensuring that our device included a full 180° arc. Later when we constructed a prototype, we were then able to test these angle allowances empirically, albeit simply. While these requirements are very important to our design, the simplicity of the measurable quantities in the specifications made us confident that even a simple test with our prototype would be sufficient to verify the specifications. With that in mind, we had members of our team attempt to use our device as intended and then measured the angles they were able to achieve for each relevant joint.

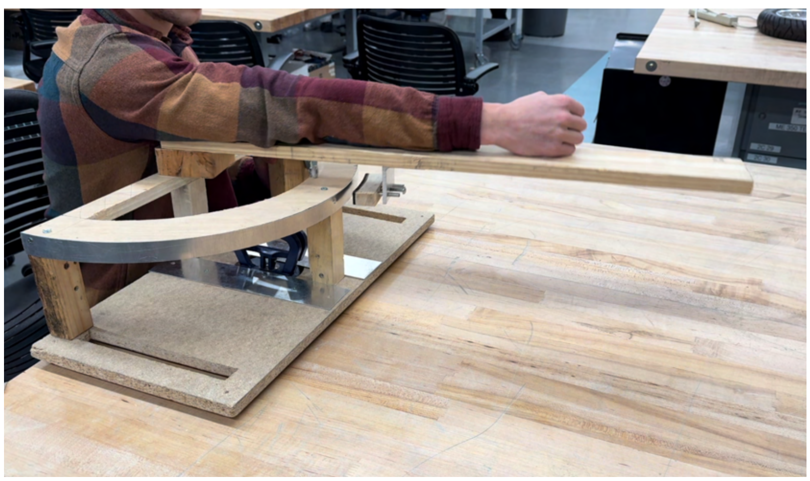


Figure 47. This figure shows the beta design being tested for shoulder range of motion.

We found that of the 180° we intended to allow, our build design only allowed users to reach a range of about 165° since the wheel element of the arm would contact the back support of the arc, preventing the full range of motion. Based on these findings, we redesigned the arc of our device to eliminate the back support that interfered with the range of motion, and now feel that we have verified these specifications through this redesign, although we also plan to run the same empirical testing with our new build design once we have constructed it.

Prehensile Grips
The specification for our next requirement was that we must allow users to work on all six of the functional prehensile grips. By basing our handle designs off of these prehensile grips, we were able to start verifying our design's ability to meet this specification through design. Since these

different grips each have very specific shapes that are associated with the grips, we felt that simply modeling our handles off of the existing shape of these types of grips was a simple and effective way to verify that our handles allow for users to work on each of their prehensile grips. To that end, our verification to date for this requirement has all been through design, first by making the decision to have different handle attachments for our device to allow users to work on different grips and then by how we chose to shape these grips. Moving forward in verifying this requirement, we are looking to start prototyping at least some of these grips and plan to show them ideally in-person but at least virtually to some medical professionals to get their perspective on our handles ability to support prehensile grip rehabilitation. At this point we are confident that by designing our handles based on the shapes necessary for each of the grips, our device does meet this specification, but we are still planning to fully verify that by reaching out to some of our stakeholders.

Measure Joint Angles

The next requirement for our device was that it must be able to measure joint angles for our users during use of the device, and the specification that was set for this requirement was that our device must be able to delineate angle measures from 0° to 180° with increments of 5°. As with some of the previous requirements, this one is very simple to verify, both through design and through simple empirical testing. During our design process we made the decision to have angle measurements on the surface of the arc to make it easy for users to see how far they are going, this served as the initial verification for this requirement.

Figure 48. This figure shows the angle markings in increments of 5 degrees drawn along the arc of the beta design.

Once our prototype was constructed, we were then able to simply verify this specification again by having members of our team use the device as intended and comparing the angle measurement values on our device to the values we found by actually measuring our proxy users.

As expected, we found that these values were nearly identical, and feel confident that the fidelity of our prototype was high enough in this regard to reasonably view this specification as verified.

Strengthening

As opposed to the verification plans discussed above for earlier requirements, the process of verifying this specification was more complex. In order to meet this specification, our device must be able to provide variable loads from 0 to 15 pounds. During our design process we were able to produce calculations using tools and equations from statics and dynamics, and our results from those calculations made us confident that our resistive element would be able to provide the range of resistance necessary to achieve the desired load range. However, given the complexity of this part of our design, we did not feel that those calculations alone were sufficient to verify this requirement. The verification of this specification was one of the driving factors in the construction of our initial prototype as one of our biggest design concerns was if the resistive element would actually function as we expected. To that end, we conducted a series of tests with different forces applied to the brake pad to determine if we could achieve the proper resistance to produce the desired load. Our initial tests to date have focused primarily on confirming that our device can produce varied loads by adjusting the force applied to the brake pad and through our testing we are confident enough in our device's ability to do so that we feel secure progressing with this design.

Figures 49 and 50. These figures show the result of tightening the bolt, bringing the brake into contact with the arc, allowing variable loads of friction to be tested.

Going forward, once we complete our final design, we plan to use a force meter to more quantitatively measure the range of forces our device can produce to determine if we are fully meeting this specification. Since our testing for this specification relies on simply measuring loads needed to use our device as intended, we feel very confident that the results of this form of testing will be valid.

Accommodation
Our next requirement was the ability of our device to accommodate users, and we were able to verify this requirement primarily through design. The main focus of this specification was for our device to be usable from the lowest extreme (women's 5th percentile wrist to grip measurement) to the highest extreme (men's 95th percentile shoulder to grip measurement) of how we intended our device to be used. We were able to verify this through design by ensuring the arm of our device was 29" long with handles that can be slid from one end of the arm to the other to allow for user adjustability. Going forward, we would like to put our device through a series of tests with a wide range of users so as to confirm that our device is in fact usable by the majority of intended users and that actual use of our device lines up with our expectations. That being said, based on our anthropological research and interviews with a variety of relevant stakeholders, at this point we feel confident in the ability of our device to meet this specification.

Safe for Users
The next requirement we had was about user safety, and the specification for that requirement was that our device must meet the CDSCO approval criteria for low-risk devices. The primary focus of those criteria is that the device not be intended to contact injured skin or to hold or modify any substances. We were able to verify this specification through design as our device is not intended hold or modify any substances, and the only contact points for our users with the device are their hands, wrists, elbows, and shoulders and we do not anticipate having any injury issues with those parts of the body that would be relevant to our device. We feel confident that if our device meets the CDSCO approval criteria, then it can appropriately be deemed safe, and based on what we can find about the CDSCO approval criteria we believe our device meets the criteria and would be approved as a low-risk device, and therefore meets this specification. As part of that approval process our device would have to go through a series of trials to prove its efficacy as well as its safety, and that is what our next steps would be to fully verify this specification.

User Comfort
Unlike some of the requirements that can be verified more trivially or at least more simply, verifying user comfort will be rather complex. The specification for this requirement is that after using our device, patients should not report higher pain than they experienced beforehand or while using other rehabilitation methods. The design of our device has no invasive or penetrative components and should not be a source of harm under supervised use. To fully verify this specification, a comparison study must be done with a number of intended users. Testers would score their comfort/pain levels before using any rehabilitation methods, use other rehabilitation methods that Poovanthi currently uses and then score their comfort, then use our device for a duration and score their comfort again. Since the testing would be done supervised, testers should feel safe. These scores would be done on the widely used numerical pain rating scale [39] and interviews would be conducted after to determine if using our device increased their pain

levels at all. This form of verification is very robust and we feel confident that the results of such a study would be valid and clearly show whether our device increases user comfort.

Affordability

The specification for this requirement is that our device must not cost our users more than 1000 Rupees ($12 USD). While we can relatively easily estimate the cost of our device based on our material choices and overall design, this is a complicated specification to robustly verify. The total cost of our device will largely depend on material selection and sourcing as well as the manner and location of manufacturing the device. At this point in time, we do not feel confident in our cost estimations, and believe an economic study or simply producing and selling our device would be necessary to fully verify this specification. Based on what we have purchased in order to construct our build design for this course, we have a cost estimate that is much higher than allowable by this requirement. That being said, we are still in the process of refining both our design and our manner of manufacturing, and the per unit cost of producing a single prototype of our device is higher than it would be with larger scale production. Additionally, the prototype we’ve already built as well as the final build design we’re planning to build for this course are meant to serve more as proofs of concept for our design than as an example of what our final design will look like. Although perhaps outside of the scope of this project, we also have discussed the possibility of our devices being purchased by the rehabilitation clinic and then rented out to users to take home during their rehabilitation as a method of reducing the cost to our intended users. With all of this in mind, while we believe that our design could meet this requirement at a later point, the current version of our device does not meet this requirement.

User Preference

The manner of verification for this next requirement is similar to that of the user comfort requirement. The specification for this requirement is that after using our device, 75% of users prefer using our device over other existing methods of rehabilitation. This specification can only be verified through a study where a number of our intended users use both our device as well as a series of other rehabilitation methods for a period of time. At the end of this trial, users would then be surveyed on whether they preferred using our device or whether they preferred the other methods. This is a fairly robust verification method, and as such we feel confident that the results of this study would be valid, and the numerical nature of these results would be very easy to interpret as the specification would either be met or not met.

Transportable

The specification for this requirement is fairly straightforward; our device must score less than a 1 on the NIOSH lifting index. Scoring something on the index involves going through and performing the calculations for the device to get the final score for the device. The NIOSH lifting index equation is LC x HM x VM x DM x AM x FM x CM = RWL where LC is the load constant (23 kg), HM is the Horizontal Multiplier factor, VM is the Vertical Multiplier factor, DM is the Distance Multiplier factor, FM the Frequency Multiplier factor, AM the Asymmetric Multiplier factor, CM the Coupling Multiplier factor, and RWL is the Recommended Weight Limit. Each of the multiplier factors are based on different dimensions that can be measured from the recommended carrying position and correlate to tables defined by the NIOSH. Based on our device we have compiled measurements that give us the various multiplier factors. The values obtained for the factors are as follows: HM is 0.83, VM is 0.85, DM is 0.65, AM is 1.00, FM is 1.00, and CM is 1.00. The Lifting Index can then be found by dividing the weight of our device by the RWL, which equals a Lifting Index of 0.365. This scale has been reviewed and studied, and so we feel confident in the validity of the scale, and thus feel confident that our score is valid, and the interpretation of the score meets our requirements.

Ease of Use

As with some of the preceding requirements, the verification process for this requirement will be fairly complex. The specification for this requirement is that at least 55% of our users be able to achieve either complete success or success with a minor issue when attempting to use our device. Based on our design, we believe that for the most part, our device should be relatively intuitive for users, however we do not think that is a sufficient method of verifying this requirement. In order to fully verify this specification, we will need to conduct a clinical study where we have some of our intended users attempt to use our device and observe how successful they are when trying to use it. Unlike some of the other verification plans involving studies, the results of this one might be harder to interpret. Evaluating whether a user achieved complete success or success with a minor issue or neither might be somewhat subjective and could make the results difficult to analyze. That being said, we believe that a study such as this should be sufficient to verify whether or not our device meets this specification.

Maintainable

This requirement is fairly straightforward, as the specifications for it are simply that any replacement parts must be available locally and that only one tool be needed to repair or assemble the device. Both of these specifications can be verified simply through design, as the first relies on the material selections and the second relies on the selection of fasteners for the device. The prototype that we have been using for testing, as well as the final build design we are planning to construct for this course, serve more as proof of the concept of our design than they do as examples of what our final design will look like. With that in mind we believe that our current materials or at least reasonable approximations of them should be available locally in India, and so we feel confident that our device will meet that specification. In terms of tooling, we have been standardizing all the fasteners in our prototype device and plan to do the same with our final design so that all the fasteners can be manipulated with the same tool. For our existing prototype that tool is a phillips head screwdriver, although for future designs we expect our fasteners to be compatible with a hex wrench rather than a screwdriver. Either way, we feel confident that our device can meet this second specification as well.

Durable

Our last requirement is that our device be durable, and the two specifications for this requirement are that our device be able withstand 100% humidity and temperatures up to 105°, as well as be able to withstand three uses a day over the course of a year. The ability of our device to withstand the humidity and temperatures in this first specification center around the materials chosen for our device. Based on our current design of primarily aluminum with some 3D printed components as well, we expect our device to be able to withstand both the humidity and temperatures required. In terms of withstanding three uses a day over the course of a year, we are similarly confident in the durability of our selected materials, but do not feel confident enough just from material selection to say our device meets that specification. In order to fully verify that specification, we would want to put our device through a series of stress and load tests, as well as drop tests to ensure its long-term durability. For stress and load tests procedures include identifying potential stress points on the device, creating a test setup that allows the controlled application of stress to the specified areas, gradual application of a load, and the documentation of the maximum stress the device can withstand. The procedures for a drop test include choosing varying drop heights that represent potential scenarios of use, setting up a controlled testing environment with a flat and hard surface to simulate impact conditions, performing drops at the identified heights, inspecting for damage, and recording results.

Validation

As detailed above, we have already verified or have plans to verify all of the requirements and specifications we've created for our design. In addition to verifying all of those however, it is also important to consider validating our project as a whole. With that goal in mind, we have made an effort to keep our primary stakeholder Dr. Shibu updated throughout our design process, showing him our ideas and progress as we go to ensure that he is aware of what we are working on. By continuing to communicate with him about what he is looking for and what we have been able to come up with, we have our primary form of validation for our project. Looking broader, the ultimate goal of validation for our project is for it to reach a point where we can actually conduct clinical studies to determine whether our device improves on existing methods of upper arm rehabilitation for those recovering from strokes. While Dr. Shibu has provided us with a number of useful requirements for our design, the primary goal of our project is to address the gap in at-home upper arm rehabilitation for those in low-income settings, and we cannot truly validate that goal without putting our device into those environments and observing the effect it has.

The advantages our design has over current rehabilitation methods is that it is not expensive, allows for users to track progression through rehabilitation, and allows strengthening of the entire arm. These features outline the gap that is being addressed with our slide board, and give an outline for what to assess during the clinical study. We have outlined a study to be performed to assess the effectiveness of the slide board.

Participants will consist of 30 patients suffering from stroke, 15 male and 15 female, who are over the age of 50 and score a 3-, 3, or 3+ on the MMT scale. The MMT scores are the target audience for our slide board, as this means users have full range of motion but not necessarily strength in their movements. These participants should be healthy apart from their stroke diagnosis and of stable mental condition. Participants are eligible if they scored more than 26 on the Montreal Cognitive Assessment and do not experience spontaneous loss of function [45]. Half of participants will be advised on how to carry out at-home exercises using dough, rubberbands, and table/counter surfaces to exercise their arms. These procedures emulate the kinds of exercises that Poovanthi might guide patients through once they leave the clinic. Participants will carry out this rehabilitation for two months [46]. The other half of participants will be given the slide board and guided on exercises to carry out for two months. At the end of the two months the two groups will test their range of motion and strength using a goniometer and by picking up dumbbells. They will also be given a survey to rate their rehabilitation experiences using the devices. The qualitative answers and quantitative measures will provide a basis for how participants feel using the standard methods for exercise versus the slide board, and how much the slide board impacts their range of motion and their strength.

During testing we plan to note what notable issues arise and then directly address them with plans for future adjustment. While we are unable within the scope of this course to conduct the full-scale testing detailed above, we were able to conduct preliminary testing with a small group of test subjects and noted their usage issues and solutions in Table 7 below. This preliminary testing consisted of verbally explaining to the subjects how to use the device and then observing how the subjects interacted with the device after their instruction. This group of subjects was not representative of our intended users, however we felt that it was reasonable to simply test if users could easily understand how to use the device.

Table 7. Results of Preliminary Testing on Usage Errors

Usage Issue	**Solution Suggestion**
Misunderstood where to put their joint therefore moved the arm incorrectly.	Instruction Manual in Appendix E or possible sticker instruction(arrow).
Oriented the device incorrectly and therefore was unable to understand how to use it.	Instruction Manual in Appendix E or trained on relevant exercises from a professional before taking home.

Did not slide handle to correct location.	Instruction Manual in Appendix E or trained on relevant exercises from a professional before taking home.

Discussion

Problem Definition

The original design problem our team faced is to devise a solution for a take home rehabilitation device that would suit a low income setting, work the entire arm, and have the ability to track progress. Due to the time constraints to a single semester, this was as far as we could diagnose the problem to give us time to develop a direction toward a solution. If we had more time and resources to continue the project, the first thing we would have done is to better define the problem with rehabilitation in India. This means conducting a lot more preliminary work such as more extensive meetings with Dr. Shibu in the early stages of the project before getting into a design. This would help us better understand the gaps in resources and where the issues really lie rather than taking a few short directions in the beginning to base the entire project off of, before being rushed to make a design. In addition to this, if we had additional resources and data such as more in depth data on the types of exercises that are needed the most in the institute as well as numerical data on the variable strengths of patients it could have helped us better target the population in the clinic. This could have steered our device towards being better for specific exercises and needs based on the priority of the patients. A question we would continue to explore is how can we make the device cheaper so the patients are more willing to purchase it or rent it out. We would do this through material experimentation and testing to ensure the decrease in cost in material does not compromise the integrity of the device.

Design Critique

A strength of our design is its rigidity in that it constrains the user to complete the exercises correctly. This contrasts from current solutions in that leaning on tables and using dough can cause harm and further injury if done incorrectly. One weakness to the design is that while still functional, it is not very stable in the vertical orientation, and the stability could be improved for the horizontal orientation as well. This could be improved from the prototype by including a clamping mechanism to keep the device fixed for easier use.

Another weakness in the design is its reliance on the user placing their joint in the correct position during the exercises. To address this, we can place a pad on the pivot point and even an arrow or sticker to make it clear that is where one must set their joint. Additionally, a user manual would be helpful to illustrate the exercises and put emphasis on their joint resting in the correct location. Something we would have done differently during the design process in hindsight is to manufacture the prototype earlier to get more early testing. This would have allowed us to recognize these weaknesses and work to address them as a design change style solution.

An aspect of the design that could be improved from the build design is the use of adjustable hard stops to ensure the user does not exceed a safe range of motion. This was initially in the design concept but never made it to the prototype. This could mean adding pegs to the outer arc on the very ends as well as water jetting holes along the arc to slide in the hard stop pegs. In addition to adjustable hard stops, our current design doesn't allow for much adjustment in height for users outside of placing the device on different surfaces. Ideally, the supports in the base of our device would allow for some degree of extension and compression such as by telescoping to allow users to use the device more easily regardless of the surface it is placed on.

Something else we can improve is the structural integrity of the 3D printed components. During further testing, some of the 3D printed handles and slider attachments proved to be weak and unreliable. A way to redesign this is to make sure they are printed on one-hundred percent infill as well as having thicker crossmembers to avoid stress fractures in bending.

Another design change we would modify is the length of the slider arm. After eliminating the door hook idea and moving to the concept of laying the device on the ground, we noticed that the reference point for the length of the arm changed from the shoulder to the back, adding a few inches to the desired maximal reach. This means the 95th percentile arm length measurement needs a few additional inches. Working off of this change, a concept that has value in exploring is an extendable arm rather than an unusually large fixed piece of aluminum track. This would allow for a much more compact design and easier transportation.

Finally, the prototype and CAD we created had the center of the arc in the wrong location. This meant that when tracing the circular path it was slightly off and began to scrape at the edges. To fix this, we simply need to move the location of the arc back slightly to correctly match with the centered arm and pivot point.

Risks

Some challenges that we encountered during our design process included trying to allow for as much adjustability for all users in as many exercises as possible as well as balancing a low cost for a functioning product. To allow for as many exercises to be performed as possible we had to consider allowing the device to be used in both horizontal and vertical directions. We tried multiple designs to allow for vertical adjustability including door hooks and suction cups but we eventually decided that if the user lays on the ground or in a bed then it can be used in the vertical direction. This is good because it lowers the needed parts which lowers the complexity of use and also the cost. A lasting risk related to the final design that will always be pertinent is that the patients misuse the device even with the included instructions. This cannot be avoided but can be minimized with in depth guidance from a medical care professional when handing off the device as well as a simple instruction manual.

Reflection

Public Health, Safety, and Welfare

The entire basis of our project was to create a device to assist patients in their at-home recovery from stroke, and so public health, safety, and welfare were central aspects of this project. There exists a significant public health issue due to the lack of low-cost at-home rehabilitation methods for upper-limb stroke recovery, and this project aimed to address that shortcoming. As with any device intended for recovery or rehabilitation, the safety of our users or those around them was paramount and so throughout the design process we made sure to consider the potential risks involved with our design.

Global Context

While our project was based through a clinic in Southern India, globally stroke affects 15 million people annually, so there are much broader potential global impacts for our project than just the clinic we worked with [1]. One of the big goals of our project was to address the lack of low-cost options for at-home upper limb rehabilitation, and the need for that sort of option is prevalent globally. Our design should be applicable in any low-resource setting, which should make it very attractive on the global market. Additionally, there are modifications that could be made to our design to introduce electrical components to gamify the rehabilitation process, which could make our device more attractive in higher-income settings as well.

Impacts of Manufacturing, Use, and Disposal

The manufacturing of our existing prototypes has not had any significant impacts socially or economically due to the small scale of our preliminary production. Our prototype of our final design was made out of aluminum, which is a relatively sustainable material as it would be durable and recyclable at the end of our device's lifetime. However, if our design were scaled and mass produced, there would inevitably be increased emissions and waste products simply from the larger scale of production, although these could be mitigated through the use of sustainable manufacturing processes and potentially through alternative material choices.

Societal Impact Tools

From the beginning of our project, we made sure to give serious consideration to the multitude of stakeholders that might be affected by our work. After developing a list of stakeholders for our project, we created a stakeholder engagement map (shown above in the Design Context section) that placed stakeholders based on their levels of power and interest in our project, and labeled each quadrant of the map. We also looked at the effects of manufacturing and disposing of our device, as well as of keeping it operational.

Effects of Culture, Privilege, and Identity

Within our team, differing identities didn't have much of an affect on the approaches our team took throughout this project. Considering that all members of our team are seniors in mechanical engineering at the University of Michigan, there was a considerable amount of overlap between each of our individual approaches as we have all had similar experiences and education during our time at the University. Our primary sponsor on the other hand is a medical doctor not an engineer, and so while he had a strong influence on the scope and problem definition for our project, his influence over the actual design and implementation of our device was considerably less. Additionally our entire team has been in Ann Arbor through the duration of this project, while our sponsor has been in India, so contact with him has been somewhat more difficult, and as a result he had less of a role in the later stages of our project.

Inclusion and Equity

In terms of power dynamics between the various entities involved in the project, the sponsors Dr. Shibu and Lucy as well as Professor Sienko had the ability to influence our project design as they possessed the power to make strategic decisions affecting the project's scope, goals, and timelines. These people also have a varying degree of influence over Poovanthi patients, the UM Global Health Initiative, and the William Davidson Institute due to their connection to these stakeholders. End users exert power over the project by providing insights and feedback regarding the project's design and functionality and through the acceptance or rejection of the final product. Each team member exerts power based on his expertise, skills, and contribution to the project. Those with specialized knowledge can influence decision-making more than those without that knowledge. Furthermore, our group possesses implicit power over the end users because we ultimately decide on the final solution. Although we are designing a product with the end user needs in mind, ultimately our solution is designed to fulfill the requirements of the ME 450 course. This is an inherent problem that cannot be eliminated fully, only minimized. The input from various stakeholders throughout this project rarely differed significantly, and so we did not have many concerns with balancing differing stakeholder ideas.

Ethics

Perhaps the most prominent ethical dilemma we faced throughout the course of this project was how to balance the competing interests of keeping the cost of our product low while still maintaining a reasonable level of efficacy for our final design. Without a high enough degree of efficacy our design wouldn't accomplish anything so we had to keep that in consideration throughout, but a big part of the goal of our project was to create a low-cost solution which presented a quandary. In the end, we decided to focus primarily on the efficacy of our solution within the scope of this course. We felt that if we could prove the validity of our concept, then later iterations and development of our idea could find ways to lower the cost through alternative material or manufacturing decisions. Additionally, we discussed the potential to alleviate some cost concerns post-production, for instance by selling our device to the clinic for more than our desired users could afford so that the clinic could then rent out our device to patients for the duration of their rehabilitation at a lower cost. Our ethics as a team that align with what is expected of us by the University of Michigan and future employers include honesty, respect, and responsibility. Differences in values may include the fact that personal ethics are more individual-centered, considering the immediate impacts on oneself, however, professional ethics consider impacts on a larger organization or community.

Recommendations

If this design is going to be produced for the market there would have to be some changes to the design. The biggest change is that in the current design, the pivot point is in the center of the back part of the base, but not the center of the arc, which causes the resistive element to provide too much resistance when the arm reaches either edge of the arc. To address this concern, the arc can be extended past the current 180° and the pivot point can be moved back to the correct center. The arc also must be extended in order to allow the device to still stand on its side properly. Another change would be to round the end of the rotating arm at the pivot point so it doesn't interfere with whatever surface it is placed on in the vertical orientation as that causes instability and restricts the motion of the arm. Additionally, while not shown in our final prototype, the stability of the device can be further improved by counterboring the holes where the baseplate connects to the supports and where the brake and wheels attach to the arm to both increase stability of the device and to prevent interference in the track for the slider. A further recommendation for a bigger picture design change may be to find a way to lower the cost of the device by removing material in non-structural locations or modifying material selection for components like the posts.

While our project focused on creating a solution for low-resource settings, we have also discussed a potential addition to the design that could make it more attractive in higher-resource settings. Our current design is purely mechanical with no electrical components, and part of the reason for this is to reduce cost. However, if a sensor were added to the pivot point to measure the angle of the arm, our device could easily be gamified. This sensor data could be used to play a number of different games by effectively using the arm of our device as the controller. While this sort of addition was outside of the scope of our project, it could further expand the target users for our device, and potentially higher profits on the more advanced device could be used to subsidize the cost of the lower-cost device to increase equity for lower-resource users.

Conclusion

This project, in collaboration with the Poovanthi Institute of Rehabilitation and Elder Care in India and the University of Michigan, aims to help bridge the gap between in-facility and at-home care for stroke survivors, specifically regarding the rehabilitation of upper limbs. In particular, it addresses the needs of stroke survivors in low-income settings.

Stroke is a leading cause of death worldwide, affecting 15 million people annually. The aftermath of a stroke often results in paralysis or difficulties moving one half of the body. Therapy methods involve regaining muscle and joint movement gradually, usually through assistance from therapists. However, the rehabilitation context in India is not ideal. After leaving, many patients are unable to continue their necessary rehabilitation exercises at home for various reasons, which hampers their full recovery. The project aims to create a take-home low-cost rehabilitation device to enhance the quality of life for stroke survivors by aiding them in regaining their ability to perform activities of daily living. The key requirements for the project include accommodating a range of motion for patients, improving functional prehensile grips, being adjustable, safe, including a strengthening component, and including a measurable progress element. Additional considerations will be made to ensure the product is affordable and preferred to previous methods to motivate patients in their recovery.

In order to create a solution with these requirements, we generated 200 design concepts using various methods including morphological matrices and design heuristics. To narrow down the selection we filtered through and eliminated ideas based on duplicates, feasibility, and fulfillment of requirements [47]. The interactive slide board was chosen as the alpha design, offering a simple, adjustable, and low-cost solution for full-arm exercise, meeting all the necessary requirements. This design's components include a rectangular base, pivot point, grip slider, different grips, angle markers, and a resistive element.

Working with a first prototype “beta design”, revealed some problems with the existing design. These problems were identified using various methods of empirical testing such as testing door hooks, a suction cup, roller wheels, and brake pad material. These tests were initially created due to our design worries of vertical adjustment and stability, the ability to slide easily, and having a safe method of variable resistance.

We created a final build design out of aluminum to continue verification of our device after the semester ends. The verification involves three main categories: verified by design, verified trivially, and verified through more involved methods. Verification methods vary, with some requirements confirmed through design considerations, while others necessitate more complex tests and studies. The ultimate validation goal is to conduct clinical studies with stroke patients to assess the device's impact on upper arm rehabilitation in low-income settings. The study design involves a diverse participant pool performing exercises with standard methods, followed by assessments and feedback to evaluate the device's effectiveness [47]. The final design has some weaknesses and critiques such as stability and the possibility of incorrect usage, but further design modifications suggested can solve these issues moving forward. Our final design ultimately addresses the overall purpose of the project to provide an at-home rehabilitation device while keeping in mind the social and contextual factors of its application in a low resource setting.

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Appendix A - Team Bios

Emerson Kekhoua (Rochester Hills, MI) - I am interested in mechanical engineering because I really enjoy physics and how mechanisms and devices work under the laws of the world we live in. Ever since I was little I was fascinated with little physics trinkets like the newton's cradle, trying to understand how physics works. I also really enjoy coming up with abstract solutions using what we know about physics to make the world a more efficient place. After college I plan on ending up in either robotics or the automotive industry where I can either design new vehicle components or a means for producing them. I also enjoy psychology so the interaction of how designs affect people as well as how engineers interact with each other in coming up with solutions is intriguing to me. This means I wish to work in design and eventually move into management of a product design team. Aside from engineering I love to play acoustic guitar, run, and go on road trips to national parks/backcountry camp with my family.

Conor McNabnay (Westlake, TX) - I chose to major in mechanical engineering because in high school I developed an interest in mechanical systems through my participation in robotics. I also took engineering courses in high school where I learned about the fundamentals of engineering by working on projects such as building dragsters, truss bridges, and bottle rockets. Throughout my time at Michigan, I have prioritized experience relating to drones, robotics, and autonomous systems. During freshman year I took the Autonomous Vehicle/Drone Engineering 100 section. I also participated on a research team that explored the use of autonomous drones to detect and suppress forest fires. In the future I wish to be working in an industry relating to autonomous and connected mobility. I would like to work for an automotive or a startup company pioneering innovation in this field. Aside from engineering, I am interested in history, geography and geopolitics. I play on the rugby team for the University of Michigan and in my free time I enjoy watching sports such as football, basketball, hockey, baseball and rugby.

Aidan Kaiser-Bulmash (Washington DC) - I've always liked building things and been interested in how things work, but it wasn't until I took a design elective course in middle school that I realized I wanted to go into engineering. Taking that class pushed me towards robotics as I then joined my middle school FLL robotics team before later joining my high school's FRC robotics team. Here at the University of Michigan, in addition to majoring in mechanical engineering, I chose to pursue a concentration in robotics and a minor in computer science. I also joined the university's MRover project team and am currently working on another capstone project through the engineering honors program to create a system to provide live occupancy tracking for rec sports facilities on campus. Outside of academics, I also work as a lifeguard for the university and I am the president of the Michigan Archery Club. After graduation this year I'm hoping to remain at the university to earn a master's degree before going into industry where I hope to work primarily on robotics and design projects.

Matthew Weerakoon (Beverly Hills, MI) - I enjoy mechanical engineering because of the applicability and knowledge it teaches me about the physical world and how it can change my perspective on anything into the framework of dynamics, heat transfer, and Newton's laws. It's interesting that we are able to put every physical phenomena into derivable equations and therefore determine information about the higher forces driving that phenomena. I am also minoring in philosophy. It's a nice break from my STEM classes and helps me think about the world from different perspectives. Overall, I love learning and discovering new ways to think about problems or real life. I have been able to use CAD in engineering courses as early as middle school and been lucky enough to work in a 3D printing lab for most of highschool, where I got to teach people 3D modeling, how to use laser cutters, and how to use a variety of other creation machines. I am not sure where I want to take my engineering career but I hope whatever field I go into I can make an impact on helping people or helping the world. I also enjoy the prospect of teaching so you might see me in a high school in the future.

Nicholas Koerper (Tiffin, OH) - I'm aware this sounds basic, but I really loved science and math growing up and trying to find solutions to complex problems. Trying to find different ways to view and attack problems was always a challenge I often looked forward to. Finding a specific path like looking to break problems down into smaller more manageable problems and setting up specific goals for each has helped me progress in all aspects of life from school to my social life to my health goals. When I began choosing a major I wanted something that would fit this mindset and also didn't narrow down my options after school. Mechanical Engineering fits this description perfectly as it allows me to learn more systematic and researched problem-solving, uses math and science to understand things more deeply, and also can be applied to almost any field after school. My future so far after school is still undecided but I am really looking forward to finding my spot and I hope that I am able to make a difference either helping people directly solve problems or creating value that betters people's livelihood. This project is especially important to me because my mom suffered a stroke a few years ago and I saw firsthand her struggles with recovery and the difficulties that she faced.

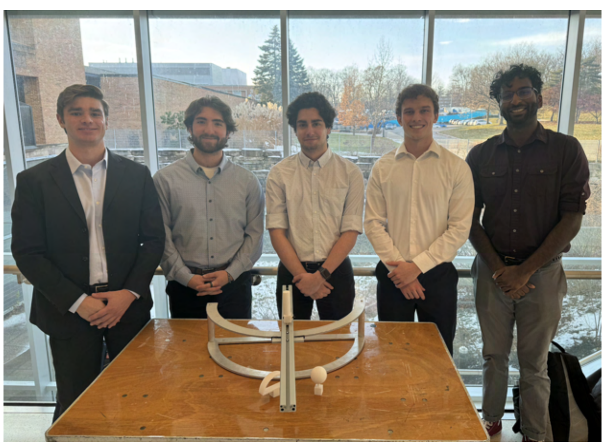


Figure A.1 Pictured left to right: Conor McNabnay, Emerson Kekhoua, Aidan Kaiser-Bulmash, Nicholas Koerper, Matthew Weerakoon

Appendix B - Generated Concepts

A solution similar to that of a fidget cube. This concept allows quick, simple, and easy to understand movements and actions which can help rehabilitate function. Varying force and size can allow extrapolation of rehabilitation to more than just the hand. This idea represents the group of ideas that are based on **handheld tools**.

Figure B.1 Fidget Cube

An idea that can help patients to work towards faster movements is speed activities, where they will be given a simple task to complete as fast as they can. This helps patients with motivation by adding a competition component, not between one another but to improve their own times. The example pictured is cup stacking in a pyramid of specific size. This idea represents the group of ideas that promote engagement and progress through **gaming interactables**.

Figure B.2 Speed Activities

One idea that would integrate the use of animals is a sort of petting zoo within the institute, where a combination of domesticated animals (commonly found in petting zoos) and trained animals would enable patients to interact with the animals, and help arm movements within a setting that may be more comfortable for the patients. This represents ideas that involve creative **things like art** into rehabilitation.

Figure B.3 Petting Zoo

An idea that encompasses a sport along with technology is the concept of a magnetic punching bag. A device inside the lining of the bag would provide a magnetic field to repulse the gloves. This would allow the patients to punch/move as they wanted, and cause no harm if they stopped. Along with other ideas, this concept is based on resistance **training.**

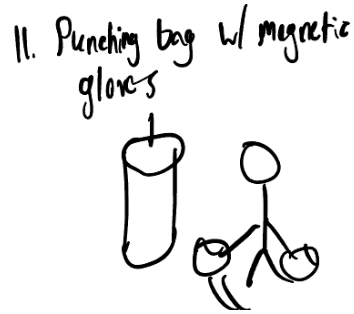


Figure B.4 Magnetic Punching Bag

Elastic gloves would help guide the extension of the hand and possibly larger gross arm movements. This could be a passive or active device, but the concept generated was to be used in a passive mode. This idea represents the group of ideas which are **wearable devices.**

Figure B.5 Elastic glove

Wearable Devices/Aid:
Wearable potentiometer: Gives real-time feedback on the intensity of movements for patients to modulate their exercise efforts.

Full bionic arm: Provides full functional assistance and motor rehabilitation.

RFID sleeve (multiple sensors): Gives feedback on range and precision of movements for the user to track progress.

Sleeve w/ haptic feedback: Gives the user tactile feedback, which helps with relearning touch sensation.

Modular exoskeleton: Assists with movement patterns to help regain functional use of the arm.

Magnet sleeve: Provides resistance that can help build strength.

Bionic Arm: Uses motor force to work with the patient's remaining arm function, providing an active rehabilitation process.

Hand exoskeleton: Provides support and assistance to boost hand and finger function during exercises.

Wearable sensors tracking ROM and degrees: Provides real-time feedback on range of motion and progress, enhancing patient awareness for self-correction.

Wearable resistive mechanism: Increases resistance during exercises for improving strength.

Smart glove: Can measure hand movements to track progress and provide real-time feedback.

Pressure sensing glove: Provides biofeedback on the force exerted during grip tasks, aiding in graded modulation of grip strength.

Voice control of glove or arm mechanism: Increases independence in controlling assistive devices, leading to an increased sense of self-efficacy.

Pneumatic therapy glove: Supporting post-stroke hand movement recovery with gradual pressure control.

Force feedback arm sleeve: Provides physical cues of the force exerted, aiding in strength and control training.

Biofeedback wristband: Provides real-time feedback on physiological parameters like heart rate and stress levels, fostering awareness of one's physical state during exercise.

Upper limb exo suit: Provides assisted movement and support for the entire arm, facilitating a wider range of exercises.

Gaming/Interactive Interfaces:
Stickers on wall (light up ball game): Encourages reaching and swatting movements to enhance range of motion and shoulder stability.

Keyboard with games (large area, far apart keys): Promotes finger dexterity and quick movements.

Fidget cubes (large): Aids in improving fine motor skills and finger dexterity along with scaling sizes.

Rock em sock em robots (mirrored movements): Facilitates mirrored movements which aid in rehabilitation and give a competitive incentive.

Putty/remote with binary game control: Enhances grip strength and executive functioning.

Movie adventure game with physical parts: Engages the user in entertaining exercises that promote gross motor skills.

Hit the drone: Promotes reaching and swatting movements, enhancing hand-eye coordination.

Operation (board game): Promotes fine motor skills and precision.

Wall of sliders/wheels: Facilitates gross motor skills like pushing or turning while standing.

Whack a mole light game: Encourages shoulder movement and hand-eye coordination as the user tries to whack the light-up moles quickly.

Dart board activity board: Helps in improving hand-eye coordination and precision.

Dominos/mini games: Encourages steady hand movements and strategy planning.

Wii bowling (video games): Promotes fun, engaging shoulder and arm exercises.

Cornhole (varying bags/weights): Enhances arm strength and hand-eye coordination through tossing bags at targets.

Interactive game-ification (Kinect): Gives an immersive virtual experience that enhances motivation and engagement in rehabilitation exercises.

Kinect game, tracks movements: Encourages larger body movements for gross motor skill improvement.

Board with sensors: Tracks user's touch, movement, and pressure levels for real-time feedback.

Electrical stimulation: Activates muscle contraction to prevent atrophy and stimulate neuromuscular control.

Ping pong: Enhances hand-eye coordination, grip control, and anticipatory skills.

Therapy Tools and Equipment:
Putty: Enhances grip strength and dexterity by changing stiffness with color transitions as visual feedback for progress.

Bounce ball between hands: Improves fine and bilateral motor skills.

Temperature: Warm conditions could increase blood flow and subsequently flexibility and movement in the affected arm.

Exercise mirrors: Assists in visually monitored practice of bilateral symmetrical exercises.

Smart textiles: Provides tactile feedback encouraging self-correction of movements.

Electrical muscle stimulation: Augments impaired muscle function to enhance movement and prevent muscle atrophy.

Rehab ball with sensors: Measures force and accuracy of movements, tracking recovery progress.

Exercise bands, putty, Legos, board games, Bop It, Rubik's Cube: Diverse manipulatives for fine and gross motor coordination, grip strength, and cognitive engagement.

Tap lights: Enhances hand-eye coordination, timing, and reaching skills.

Squeeze remote: Encourages hand strength, grip control, and motor planning.

Needle gauge: Enhances fine motor skills and coordination.

Inflatable: Creates varying levels of resistance for muscle strengthening.

Simulators:
VR/AR apparatus (immersive): Creates engaging and motivating environments for practice of functional tasks.

Motion capture within clinic: Allows therapists to monitor patient's movements and plan appropriate exercises.

Driving simulator (wheel): Exercises arm and shoulder rotation within a functional context.

Wearable AR sensors: Augments traditional exercises through visually guided tasks in an enhanced reality setting.

AR rehab exercises: Provides an engaging platform for functional, real-world activities in a controlled environment.

VR rehab environment: Provides a virtual setup for performing guided exercises, increasing motivation and consistency.

VR (cardboard helmet): Offers affordable and portable immersion in virtual environments for therapy.

Cooking simulator (or not): Develops dexterity, coordination, and bilateral hand use in a functional context.

Simulated sports: Provides a fun, competitive environment for gross motor skills and hand-eye coordination.

Virtual/Digital Guidance:
Dance Dance Revolution with arms/buttons: Promotes coordination and rhythm, improving movement fluidity.

AI-based app (like Peloton): Creates a competitive environment leading to increased motivation for exercising.

Holographic therapist recordings: Facilitates independent practice with guided exercises.

Music table (DJ volume sliders): Exercises fine motor control and rhythm through fun, engaging musical activities.

Phone as sensor (app): Provides an accessible platform for gamified therapy at home.

Group Simon says: Offers a social aspect to therapy, leading to increased motivation.

Headphone puzzle listening: Trains arm control and coordination while using hands to adjust headphones.

Video/phone detection (Xbox kinect): Allows more immersive and large-body movements, engaging the whole body in functional tasks.

Smartphone integration: Makes therapy more accessible and convenient through portable and personalized apps

Gesture recognition: Can monitor quality of movement and provide feedback for self-correction.

Visual Guidance w/ AI assistance: Uses artificial intelligence to guide patients through exercises in real-time, providing immediate feedback for optimal performance.

Therapy app: App that has personalized rehab exercises and tracks performance over time, increasing adherence to therapy.

Vibration feedback: Enhances sensory awareness and can provide cues for movement initiation and completion.

Motion capture exercise mirror: Allows for real-time visual feedback to maintain optimal posture and movement symmetry.

App (virtual therapist): Provides guided rehabilitation sessions on a digital platform accessible at home.

Rock Band, Guitar Hero, Xbox Kinect: Gamifies rehabilitation exercises, enhancing engagement and motivation.

Art and Craft Activities:
Paint by numbers: Encourages precision, control, and grip stability.

Clay: Helps in improving hand strength and dexterity through molding and shaping activities.

Personal plant (bonsai): The careful hand movements needed for bonsai cultivation aids in enhancing fine motor control.

String art: Enhances precision, patience, and hand-eye coordination.

Sorting Candy: Enhances hand-eye coordination and grip control.

Music-enhanced therapy: Motivates patients and may provide rhythmic cues for timing and coordination of movements.

Cup stacking: Fosters dexterity, coordination, and sequencing skills.

Knitting: Improves dexterity, coordination, and the therapeutic benefit of repetitive tasks.

Art (Bob Ross): Enhances fine motor control, creativity, and a sense of accomplishment.

Petting zoo: Promotes gentle, controlled movements and tactile sensory experiences in a calming environment.

Resistance/Strength Training:
Hydro pad: Gives resistance training to build strength and endurance in water.

Shadow boxing: This mimics real-time boxing moves, promoting arm strength and coordination.

Arm wrestling robot: Offers progressive resistance training for arm strength

Handle grippers: Aids in re-establishing grip strength.

Actual hand powered bike: Provides a total upper body workout, improving endurance.

Fast bag boxing: Enhances speed, reaction time and coordination.

Large book: Promotes extended arm holding, improving arm strength.

Rope cycle: Provides progressive resistive exercises for arm and shoulder, improving strength and endurance.

Weights: Helps improve arm strength and endurance.

Fluid tank with challenges inside: Introduces a unique resistance for building strength and control, while also promoting daily living skills.

Grip trainer: Specific tool to boost hand strength and dexterity by resisting against grip.

Magnetic resistance therapy: Provides a non-contact method for resistance training, useful for gentle strength-building exercises.

Exercise class/competitions: Encourages social interaction, competition, and peer support in rehabilitation.

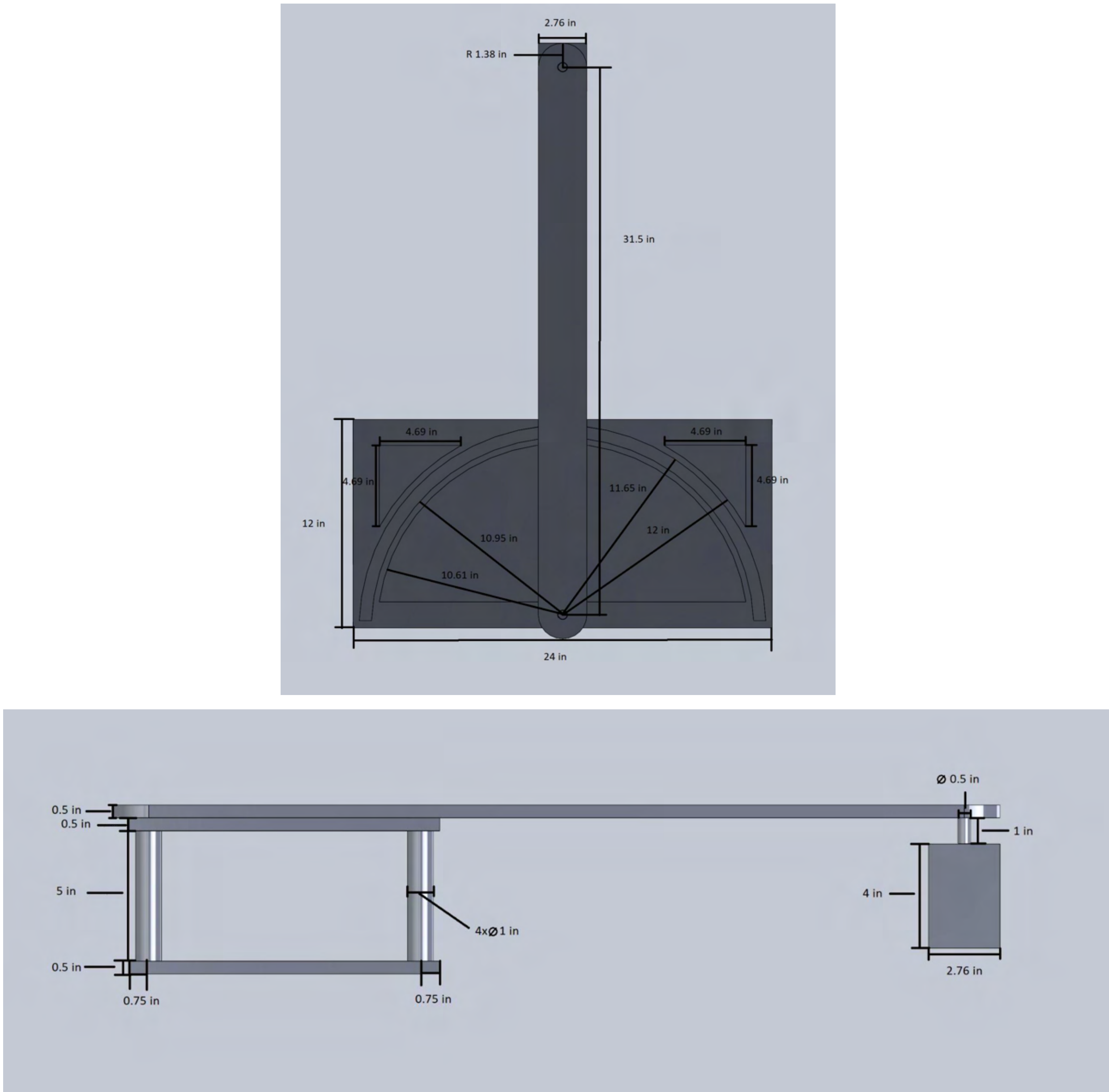
Pulleys: Assists in active-assistive movements for improving range of motion.

Magnetic gloves/electromagnet: Creates resistive force for strength training of the fingers and hand.

Punching bag with magnetic gloves: Enhances strength and aerobic conditioning, while also honing coordination and timing.

Stretch/resistance machine: Offers adjustable resistance for progressive muscle strength and endurance building.

Appendix C - Detailed Alpha Design Measurements



Figures C.1. In depth dimensionally annotated CAD of the alpha design details the thickness of each member at .5" as well as the tentative radii of the track and rotating arm edges.

Appendix D - Build Description

Bill of Materials

Item	Quantity	Source	Catalog Number	Cost	Contact
1.50” X .75" Smooth Surface T-Slotted Profile - Single Open T-Slot	1 (36” long)	80/20	1575	31.25	1575 | 1.50” X .75" Smooth Surface T-Slotted Profile - Single Open T-Slot (8020.net)
0.25” Aluminum Plate 6061-T651	1 (24” x 24”)	Online Metals	1248	153.27	Order 0.25" Aluminum Plate 6061-T651 Online, Thickness: 1/4" (onlinemetals .com)
2” x 4” x 0.25” Aluminum Angle 6063-T52	1 (12” long)	Online Metals	14689	27.78	2" x 4" x 0.25" Aluminum Angle 6063-T52 | Online Metals
1” Aluminum Round Bar 6061-T6511-Extruded	1 (36” long)	Online Metals	1090	23.70	1" Aluminum Round Bar 6061-T6511-Extruded | Online Metals
By-Pass Closet Door Top Hung Back Rollers and Brackets	1 (2 pack)	Home Depot		6.67	Prime-Line By-pass Closet Door Top-Hung Back Rollers and Brackets

					(2-pack) N 6517 - The Home Depot
4-¼ in x 6 in Beige Rectangular Felt Heavy Duty Self-Adhesive Furniture Sheet	1 (2 pack)	Home Depot		4.47	Everbilt 4-1/4 in. x 6 in. Beige Rectangular Felt Heavy-Duty Self-Adhesive Furniture Sheet (2-Pack) 49950 - The Home Depot

Brake Manufacturing Plan

MANUFACTURING PLAN
RAW MATERIAL STOCK: 1/4" ALUMINIUM SHEETE

Step	Process Description	Machine	Fixture	Tool(s)	Speed (RPM)
1	Use the waterjet to cut the part to the final shape	Waterjet			
2	Position the part with the top face up in the mill	Mill	Vise		
3	Use the edge finder to zero the part at a corner	Mill	Vise	Edgefiner	1000
4	Install a drill chuck and center drill, and center frill the first 0.125" hole	Mill	Vise	Drill Chuck, #3 Center Drill	1200
5	Install a 1/8" drill bit into the drill chuck and drill a hole with a depth of 3/8"	Mill	Vise	Drill Chuck, 1/8" drill bit	1200
6	Repeat steps 4 and 5 for the other 0.125" diameter hole	Mill	Vise	Drill Chuck, 1/8" Drill bit, #3 Center Drill	1200

L Bracket for Brake Manufacturing Plan

MANUFACTURING PLAN
RAW MATERIAL STOCK: 4" X 2" X 12" ALUMINUM L BRACKET

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Use the horizontal bandsaw to cut the 4" by 2" L bracket to a length of 1.625" then deburr	Horizontal Bandsaw		Deburring Tool	300 ft/min
2	Mount in the mill with the top side facing up and the cut side facing out, on parallels with a 1/8" overhang and install workstop	Mill	Vise, Workstop	3/4" parallels	
3	Install the endmill, touch off the part and face the cut side of the part with a pass of 0.02"	Mill	Vise, Workstop	3/4" endmill, 1/2" collett, 3/4" parallels	500
4	Remove and Deburr the part			Deburring Tool	
5	Zero the Mill and measure the part	Mill	Vise, Workstop	Calipers	
6	Bring the part to the final length of 1.5" with passes of 0.05" or smaller	Mill	Vise, Workstop	3/4" endmill, 1/2" collett, 3/4" parallels	800
7	Position the part with the front face up in the mill and use the edgefinder to zero the mill at the top right corner of the front face of the part	Mill	Vise, Workstop	1/2" Collett, Edgefinder, 1" parallels	1000
8	Use the digital readout to locate the mill where the 0.150" hole is to be drilled	Mill			
9	Install a #3 center drill in the drill chuck and center drill the 0.150" hole on the front face	Mill	Vise, Workstop	Drill Chuck, #3 Center Drill, 1" parallels	1200
10	Install a #25 drill bit and drill a through hole	Mill	Vise, Workstop	Drill Chuck, #25 Drill Bit, 1" Parallels	1200
11	Use a 10-24 Tap to tap this hole	Mill	Vise, Workstop	10-24 Tap, Tap Handle	
12	Repeat Steps 8-10 for the 0.125" diameter holes, instead using a 1/8" drill bit	Mill	Vise, Workstop	Drill Chuck, 1/8" dribb bit, 1" Parallels	1200
13	Reorient the part with the top face facing upwards				
14	Use the edgefinder to zero the mill at the bottom right corner of the top face of the part	Mill	Vise, Workstop	1/2" Collett, Edgefinder, 1" parallels	1000
15	Use the digital readout to find the location that the first 0.201" hole to be drilled	Mill			
16	Install a #3 center drill and center drill the first 0.201" hole	Mill	Vise, Workstop	Drill Chuck, #3 Center Drill, 1" parallels	1200
17	Install a #7 drill bit and drill a through hole	Mill	Vise, Workstop	Drill Chuck, #7 Drill Bit, 1" Parallels	1200
18	Repeat steps 15-17 for the other 0.201" hole on the top face of the part	Mill	Vise, Workstop	Drill Chuck, #7 Drill Bit, 1" Parallels, #3 Center Drill	1200

L Bracket for Wheels Manufacturing Plan

MANUFACTURING PLAN
RAW MATERIAL STOCK: 4" X 2" X 12" ALUMINUM L BRACKET

Step	Process Description	Machine	Fixture	Tool(s)	Speed (RPM)
1	Use the horizontal bandsaw to cut the 4" by 2" L bracket to a length of 1.625" then deburr	Horizontal Bandsaw		Deburring Tool	300 ft/min
2	Mount in the mill with the top side facing up and the cut side facing out, on parallels with a 1/8" overhang and install workstop	Mill	Vise, Workstop	3/4" parallels	
3	Install the endmill, touch off the part and face the cut side of the part with a pass of 0.02"	Mill	Vise, Workstop	3/4" endmill, 1/2" collett, 3/4" parallels	500
4	Remove and Deburr the part			Deburring Tool	
5	Zero the Mill and measure the part	Mill	Vise, Workstop	Calipers	
6	Bring the part to the final length of 1.5" with passes of 0.05" or smaller	Mill	Vise, Workstop	3/4" endmill, 1/2" collett, 3/4" parallels	800
7	Mount the part in the mill with the back side facing up, on parallels and use the edgefinder to zero the part at the bottom left corner of the part	Mill	Vise, Workstop	3/4" parallels, edgefinder	1000
8	Use the digital readout to bring the mill to the position of the first 0.201" diameter hole	Mill	Vise, Workstop	3/4" parallels	
9	Install a drill chuck and #3 center drill into the mill and center drill the hole	Mill	Vise, Workstop	3/4" parallels, #3 Center drill	1200
10	Install a #7 drill bit into the drill chuck and drill a through hole	Mill	Vise, Workstop	3/4" parallels, #7 Drill bit	1200
11	Repeat steps 8-10 for the second 0.201" diameter hole	Mill	Vise, Workstop	3/4" parallels, #3 Center drill, #7 Drill bit	1200

Post Manufacturing Plan

MANUFACTURING PLAN
RAW MATERIAL STOCK: 12" long Aluminium 1" diameter round stock

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Cut the 1" diameter round stock 1/8" over the finished length	Horizontal Bandsaw			
2	Set the collet stop in the 1" collet, then thread the 5C collet in the collet block and tighten the part	Lathe	Collett Block	5C Collet	
3	Install the turning and facing tool onto the tool post and lock into place	Lathe	Collett Block	Cutting attachment, facing attachment, Turning Tool	
4	Turn on the spindle then touch off on the end face of the part, set the digigal readout to zero	Lathe	Collet Block, Collet	Cutting attachment, facing attachment, Turning Tool	750
5	Bring the part to length with passes of 0.015"	Lathe	Collett Block, Collett	Cutting attachment, facing attachment, Turning Tool	750
6	Install the drill chuck, then install the #3 center drill then center drill the face of the part	Lathe	Drill Chuck	#3 Center Drill	1200
7	Install a #25 (0.1495") drill bit into the drill chuck and drill a hole to the depth of 3/8"	Lathe	Drill Chuck	#25 Drill bit	1200
8	Install the 10-24 tap into the tap handle and the tap handle centering guide inot the chuck in the tail stock, then tap the 0.1495" hole	Lathe	Tap Handle Centering Guide	Tap Handle, 10-24 tap	
9	Repeat steps 6-8 for the other base of the cylinder	Lathe	Tap Handle Centering Guide, Drill Chuck	Tap Handle, 10-24 tap, #3 Center Drill, #25 Drill Bit	1200

SHEET 2 OF 2

Long Post Manufacturing Plan

MANUFACTURING PLAN
RAW MATERIAL STOCK: 12" Aluminium 1" diameter Round Stock

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Cut the 1" diameter round stock 1/8" over the finished length	Horizontal Bandsaw			
2	Set the collet stop in the 1" collet, then thread the 5C collet in the collet block and tighten the part	Lathe	Collett Block	5C Collet	
3	Install the turning and facing tool onto the tool post and lock into place	Lathe	Collett Block	Cutting attachment, facing attachment, Turning Tool	
4	Turn on the spindle then touch off on the end face of the part, set the digigal readout to zero	Lathe	Collet Block, Collet	Cutting attachment, facing attachment, Turning Tool	750
5	Bring the part to length with passes of 0.015"	Lathe	Collett Block, Collett	Cutting attachment, facing attachment, Turning Tool	750
6	Install the drill chuck, then install the #3 center drill then center drill the face of the part	Lathe	Drill Chuck	#3 Center Drill	1200
7	Install a #25 (0.1495") drill bit into the drill chuck and drill a hole to the depth of 3/8"	Lathe	Drill Chuck	#25 Drill bit	1200
8	Install the 10-24 tap into the tap handle and the tap handle centering guide inot the chuck in the tail stock, then tap the 0.1495" hole	Lathe	Tap Handle Centering Guide	Tap Handle, 10-24 tap	
9	Repeat steps 6-8 for the other base of the cylinder	Lathe	Tap Handle Centering Guide, Drill Chuck	Tap Handle, 10-24 tap, #3 Center Drill, #25 Drill Bit	1200

SHEET 2 OF 2

Slider Arm Manufacturing Plan

MANUFACTURING PLAN
RAW MATERIAL STOCK: 36" 8020 SLOTTED ALUMINUM

Step	Process Description	Machine	Fixture	Tool(s)	Speed (RPM)
1	Use the horizontal bandsaw to bring the part to 1/8" over the finished length	Horizontal Bandsaw			300 ft/min
2	Secure the part in the vise on 3/4" parallels	Mill	Vise	3/4" parallels	
3	install the 3/4" endmill in the 1/2" collet, touch off the part and face the cut side of the part with a pass of 0.02"	Mill	Vise	3/4" endmill, 1/2 collet, 3/4" parallels	800
4	Remove, deburr and measure the part	Mill	Vise	Deburring tool, Calipers	800
5	Zero the mill then bring the part to final length with passes of 0.05" or smaller	Mill	Vise	3/4" endmill, 1/2" collet	800
6	Use the edge finder to zero the part at the bottom right corner of the part	Mill	Vise	Edgefinder, 1/2" collet	1000
7	Use the digital readout to find the location of the 0.150" hole, then install a drill chuck, a #3 center drill and center drill the hole	Mill	Vise	#3 Center Drill, Drill Chuck	1200
8	Install a #25 drill bit and drill a through hole in the part	Mill	Vise	#25 Drill bit, Drill Chuck	1200
9	Install a #3 center drill and center drill each 0.201" diameter hole	Mill	Vise	#3 Center Drill, Drill Chuck	1200
10	Install a #7 drill bit and drill through holes at the location of each 0.201" diameter hole	Mill	Vise	#7 Drill bit, Drll Chuck	1200

Arc Manufacturing Plan

Raw Material Stock: 2” x 2” 0.25” Aluminum 6061-T651

Step	Process Description	Machine
1	Use the waterjet to cut the 2’ x 2’ x 0.25” Aluminum Plate into the shape of the arc with three holes	Water Jet

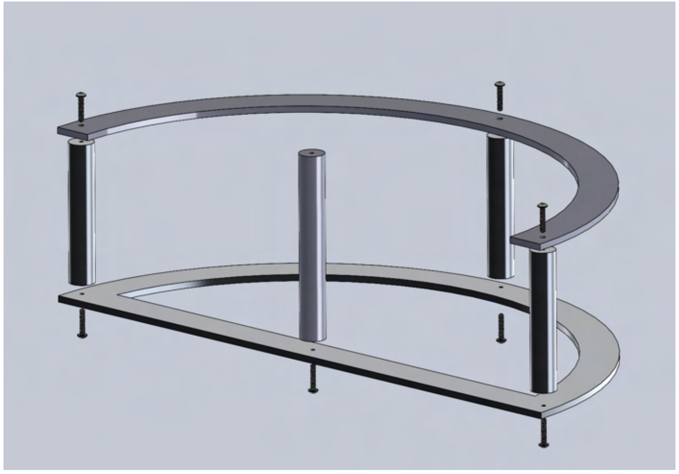
Baseplate Manufacturing Plan

Raw Material Stock: 2’ x 2’ x 0.25” Aluminum 6061-T651

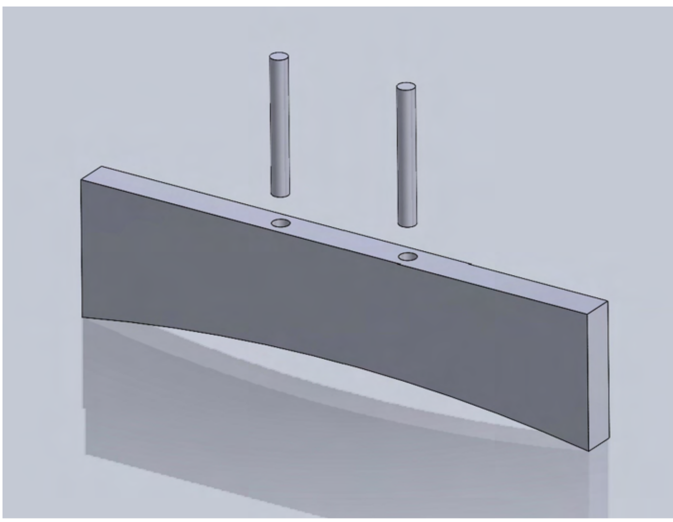
Step	Process Description	Machine
1	Use the waterjet to cut the aluminum plate into the shape of the baseplate with four holes	Water Jet

Assembly Plan

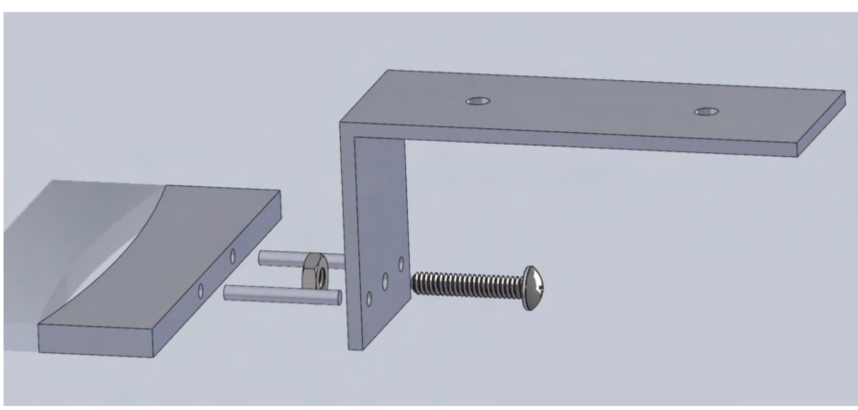
1. Attach the bottom of the three 5” posts to the baseplate with 10-24 screws
2. Attach the 7.25” post to the baseplate with a 10-24 screw
3. Attach the tops of the three 5” posts to the arc with 10-24 screws



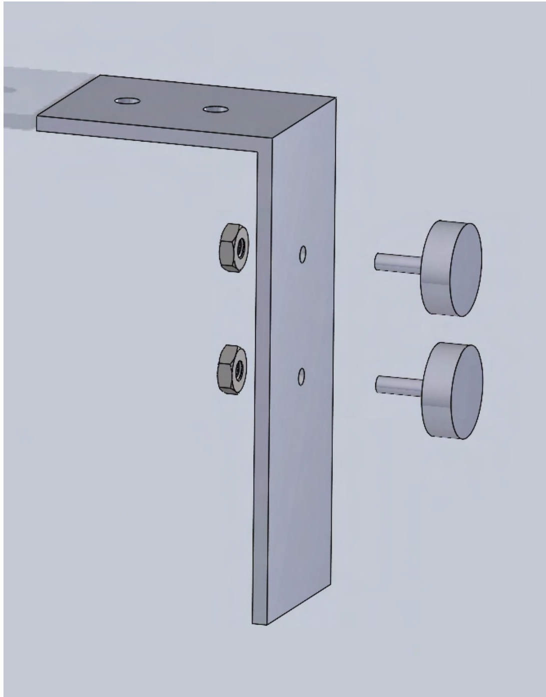
4. Press a ⅛" dowel pin into each hole of the brake



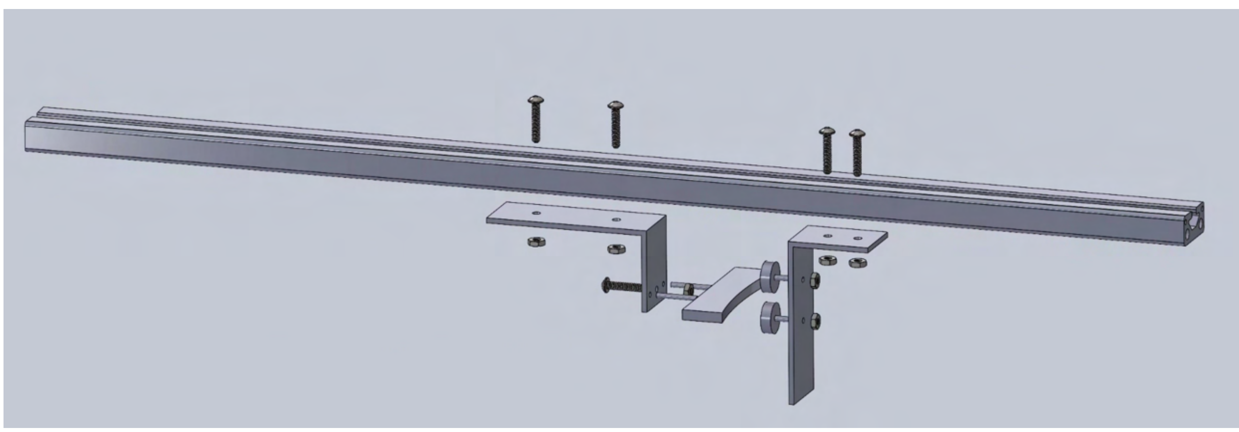
5. Insert the dowel pins into the holes on the L bracket for brake
6. Screw a 10-24 bolt into the threaded hole in the L bracket for brake
7. Attach a nut to the end of the bolt



8. Attach the wheels to the L bracket for wheels



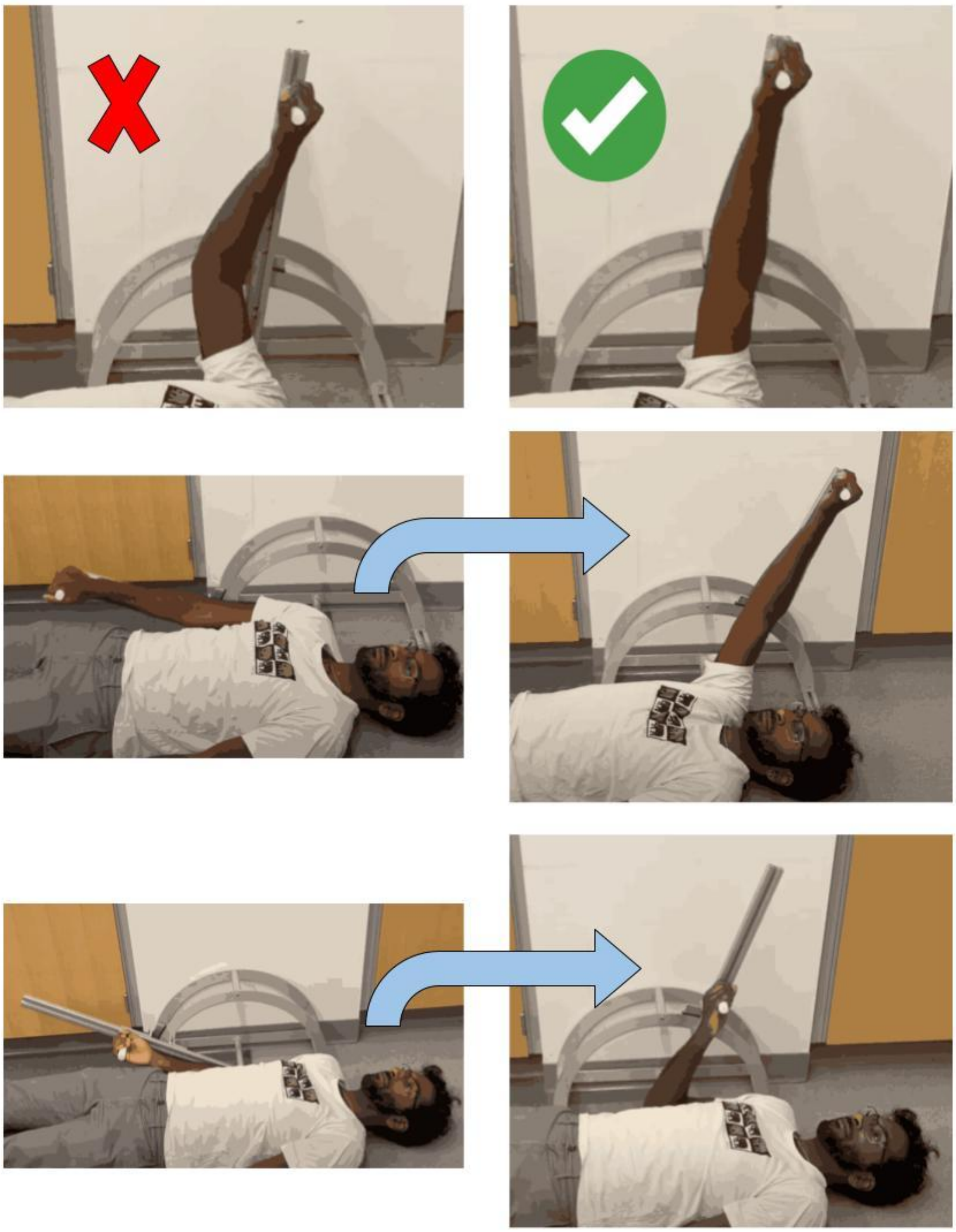
9. Attach the L bracket for wheels to the slider arm with two 10-24 screws and nuts
10. Attach the L bracket for brake to the slider arm with two 10-24 screw and nuts



11. Attach the Slider arm to the long post with a 10-24 screw

Appendix E - Instruction Manual

For vertical exercises:



Horizontal Exercises

For wrist:

For elbow:

For shoulder:

To increase resistance: