Massage Gun Redesign

Final Report

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M E 392M 6: Engineering Design Theory and Mathematical Techniques

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INTRODUCTION

To reverse engineer something is to predict how it functions, physically dissect it to understand its internal workings, and then decide which functions, subsystems, or qualities needs to be improved. For this project, I chose an inexpensive massage gun purchased off an online ecommerce site. This device is for therapeutic applications to help people with post workout recovery, chronic pain, or for those who enjoy self-controlled massages. This report will cover the inception of the product idea through different design avenues for the device.

Mission Statement

To start to understand the massage gun, a mission statement needed to be established for the device. The product description is as follows:

A compact, high-powered percussive therapy device that offers deep muscle relief from linear actuation with different attachments.

This description envelopes all the main characteristics and purpose of the massage gun. Following this description, Table 1 below contains the different markets that this device is marketed to, the assumptions of what the device inherently should have, the stakeholders, and initial ideas of avenues for creative design. Some things to highlight from the table are the avenues for creative design. Points of interest for this device are the user interface, the mechanism for linear actuation, the control system, and the ergonomics. These points helped establish an understanding of which directions to pursue when asking questions to myself and to others.

Table 1. Mission statement in tabular form.

Primary Market	Massage enjoyers	Athletes	Physical therapy patients	People with chronic pain
Secondary Market	Spas	Hotels and resorts	Sports teams	Retailers specializing in health and wellness products
Assumptions	Compact	Ergonomic	Multiple settings using an interface	`Portable
Stakeholders	Customers	Employees of company	Suppliers and manufacturers	Retailers and distributors
Avenues for Creative Design	Different styles of user interfaces	Mechanism design for actuation movement	Control system design for different movement patterns	Design for ergonomics

<u>Technical Questioning</u>

To better understand the massage gun, questions were asked to clarify what tasks needed to be accomplished. In Table 2 below is a tabularized set of questions and answers. This task clarification established the goals, possible performance metrics, limitations, expectations, and design avenues.

Table 2. Task clarification for massage gun redesign.

What is the problem really about?	The goal for this project is to develop a system to vary the movement of a massage gun's actuator to give the user a more soothing experience.
What implicit expectations and desires are involved?	It is expected that the enhanced massage gun will not harm the user. Also, the solution should not be unreasonably expensive.
What avenues are open for creative design?	There are many movement patterns that can be created with varying motion of an actuator. Design of a mechanism that creates a different actuation movement. Control system design to create different movement patterns. Different geometric design of attachments. Ergonomic design for handle. User interface design for user setting control.
What avenues are limited or not open for creative design? Limitations on scope?	The solution must be compact enough to fit in a standard sized massage gun. Must be able to do this in one semester.
What characteristics/properties must the product have?	Compact. Ergonomic design. Multiple speed/force settings.
What aspects of the design task can and should be quantified now?	Force vs. speed plots, movement patterns from position vs time plots (time domain), FFTs to see most prominent frequencies
Do any biases exist with the chosen task statement or terminology? Has the design task been posed at the appropriate level of abstraction?	Yes, I chose this product because of my interest in massages. I believe the task poses an appropriate level of abstraction. The goal for this project is to make the user have a better experience, that being either with different actuation patterns, force output, different attachments, or the ergonomics of the massage gun.
What are the technical and technological conflicts inherent in the design task?	The design of a control system and mechanism for different actuation patterns and movements will be difficult. Developing the appropriate trajectory for the mechanism and creating a system for changing the movement patterns through open loop control will be challenging.

CUSTOMER NEEDS

After asking internal questions, doing external questioning was the next step. Interviews were conducted to gather the best information about what can be done to improve the massage gun. Many kinds of people were interviewed for this customer needs analysis due to the massage gun's many applications. I categorized the people into a few groups: Massage Enjoyer, Athlete, Chronic Pain Suffer.

The first group of people, Massage Enjoyer, are those who enjoy the feeling of massages and receive them mostly for relaxation purposes. The Athlete group consisted of people who use massage guns for post workout relief and lactic acid dissipation. Lastly, the Chronic Pain Sufferer group are people who have medical conditions that cause physical external pain and desire pain relief. Identifying these different groups was straightforward because of the wide range of age groups and occupations I interviewed. Most of the interviewees were college students, and a minority were employed middle-aged people.

Interviews

The procedure during the interviews were as follows:

1. Ask if they have used a massage gun before.
    a. If yes, ask why and how they used it.
    b. If the price reflected the value of the product.
    c. What features they liked most about it.
2. Let them use the massage gun and all the different attachments.
    a. Do not help them at first with how to turn the device on and press down with a force to amplify the speed.
        i. If they are confused after a minute, tell them how to use the interface.
    b. Ask if the interface is confusing, even if they can turn it on.

   c. Let them use the massage gun for a few minutes and observe their facial and physical reactions without asking them.
3. After using the device, ask them questions:
   a. “What do you like about the product?”
   b. “What do you not like about the product?”
   c. Ask about features: “What do you think about the:”
      i. Material
      ii. Handle
      iii. Interface
      iv. Intensity
   d. “What kinds of improvements would you make for this device?”

After each question, the main points that the interviewee brought up were written down in a table to later be categorized. The “sticky note” technique was used to organize the needs by making columns of the interpreted needs on the Miro software.

Customer Needs Analysis

Below, Table 3, is my interpreted needs list. The top weighted customer needs are Actuation Speed of the massage gun and Intuitive Interface. Many of the people I interviewed were surprised about how fast the massage gun actuated when they first pressed it against their bodies. Those who used a massage gun before tended to enjoy this realization while those who are not as familiar with these kinds of devices indicated distress. Many comments were on this feature which can be improved upon by either decreasing or increasing the max speed. The interface for this device is simple yet can be confusing. Everything is controlled by one button that needs to be pressed in different ways for different commands. One button pressed on the device shows the battery power and to turn on the motor, the user needs to hold down the button. Many people did not like that fact and found it quite confusing. A system with more indicators and switches is something that can be done to improve this feature.

Table 3. Interpreted customer needs list.

Massage Gun: Customer Requirements to Address

	Customer Requirement	Weight	Raw
I.	**Massage Gun Body**		
	A. Compact	3	11
	B. Lightweight	2	7
	C. Body Material Quality	3	11
II.	**Ergonomics**		
	A. Handle size	2	4
	B. Handle grip	2	8
III.	**Interface and Control**		
	A. Intuitive Interface	4	14
	B. Intensity Control	2	5
	C. Informative Interface	2	4
	D. Intensity Settings	2	8
IV.	**Performance**		
	A. Actuation Speed	5	18
	B. Stroke Length	3	10
	C. Human Body Range	2	4
	D. Battery Life	1	2
V.	**Attachments**		
	A. Attachment Indication	2	7
	B. Attachment Geometry	3	9
	C. Attachment Material	1	2
VI.	**Cost**		
	A. Low Cost	2	6

Key:

5	Must
4	Good
3	Should
2	Nice

The frequency of customer needs was used to quantify the importance of each need. To change the raw frequency, a mapping function needed to be used. Equation 1, (Rosetta Code, 2024) below is a simple mapping equation that converts one range to another range. Seen in Table 3, the maximum number of instances of a need was Actuation Speed with a score of 18. The least frequency of a need was Attachment Material with a score of 2. These maximum and minimum frequencies were then mapped to a range between 1 and 5 and rounded up to the nearest integer. The key under Table 3 shows the meaning behind each weighted score with 5 meaning that need must be addressed to 2 meaning it would be nice to address that need but it is not necessary.

$$t = b_1 + \frac{(s-a_1)(b_2-b_1)}{(a_2-a_1)} \tag{1}$$

Where a_1 and a_2 are the minimum and minimum for the original set respectively, b_1 and b_2 are the minimum and maximum for the new set respectively, and s is the value from the original range to map to the new range.

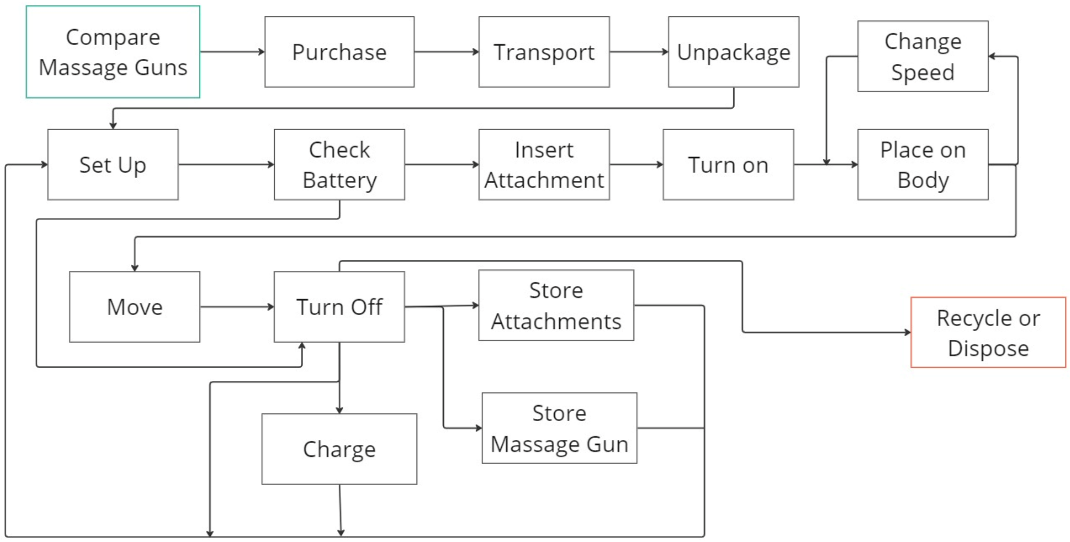
PREDICTED FUNCTIONAL MODELING

Functional modeling is an important step in the design process because it allows for the breakdown of a complicated problem to more simple sub-problems. This method was used before the massage gun was disassembled to predict how it functioned and then after the disassembly to capture exactly how the device worked.

Activity Diagram

An activity diagram is the first step for function modeling. Figure 2 below shows the sequence that a user would follow from the start and end of their experience with the massage gun. Firstly, the user would compare different massage guns either online or in person by looking at reviews or using the different massage guns in person. After this initial stage, the user will purchase, transport, unpackage, and then set up the massage gun. At this point in the activity process, there are multiple paths that can be taken. The user will first check the battery by clicking the control button once. If the battery is out of power or is low, the user will turn off the device and then charge it. If there is sufficient power in the device, the user will insert an attachment, turn it out, then place it on their body. There is a closed loop here where the user can change the speed of the actuation and then place it on their body again. After this closed loop area, the user will move the device on their body for their massage. After this stage in the process, the user will turn off the massage gun to then be stored, charged, or recycled/disposed. The user can also set up the massage gun and go through this process again.

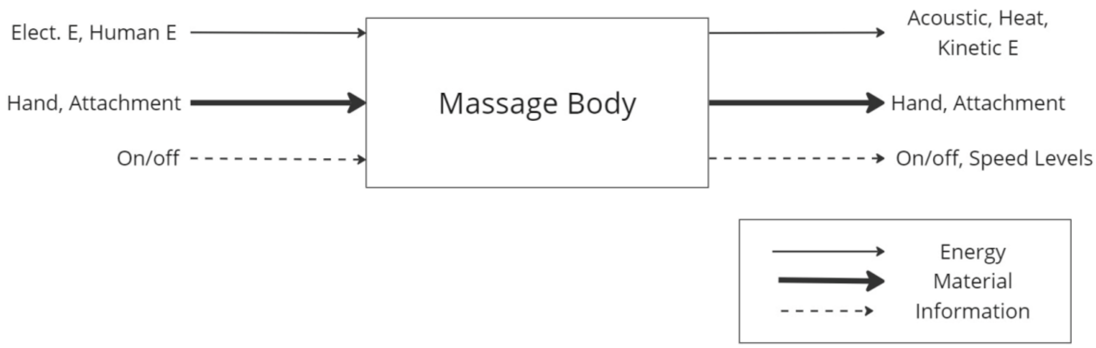
Figure 2. Activity diagram for the massage gun.



<u>Blackbox Diagram</u>

The second step for functional modeling is to create a Blackbox diagram of the system to simplify what the different inputs and outputs are for its main function which is in the center of the box. Below is Figure 3 which shows the primary function of the massage gun, being to massage a human body. The energy inputs on the left are electrical from the battery and human for holding the massage gun. The materials are a hand and an attachment. Finally, the information input for the system is on/off from a button. The energy outputs of this system are acoustic and heat from the motor, and kinetic energy from the exported force into a body. The output materials are the same as the inputs, a hand, and an attachment. The output information is again on/off and now speed levels from different LED lights.

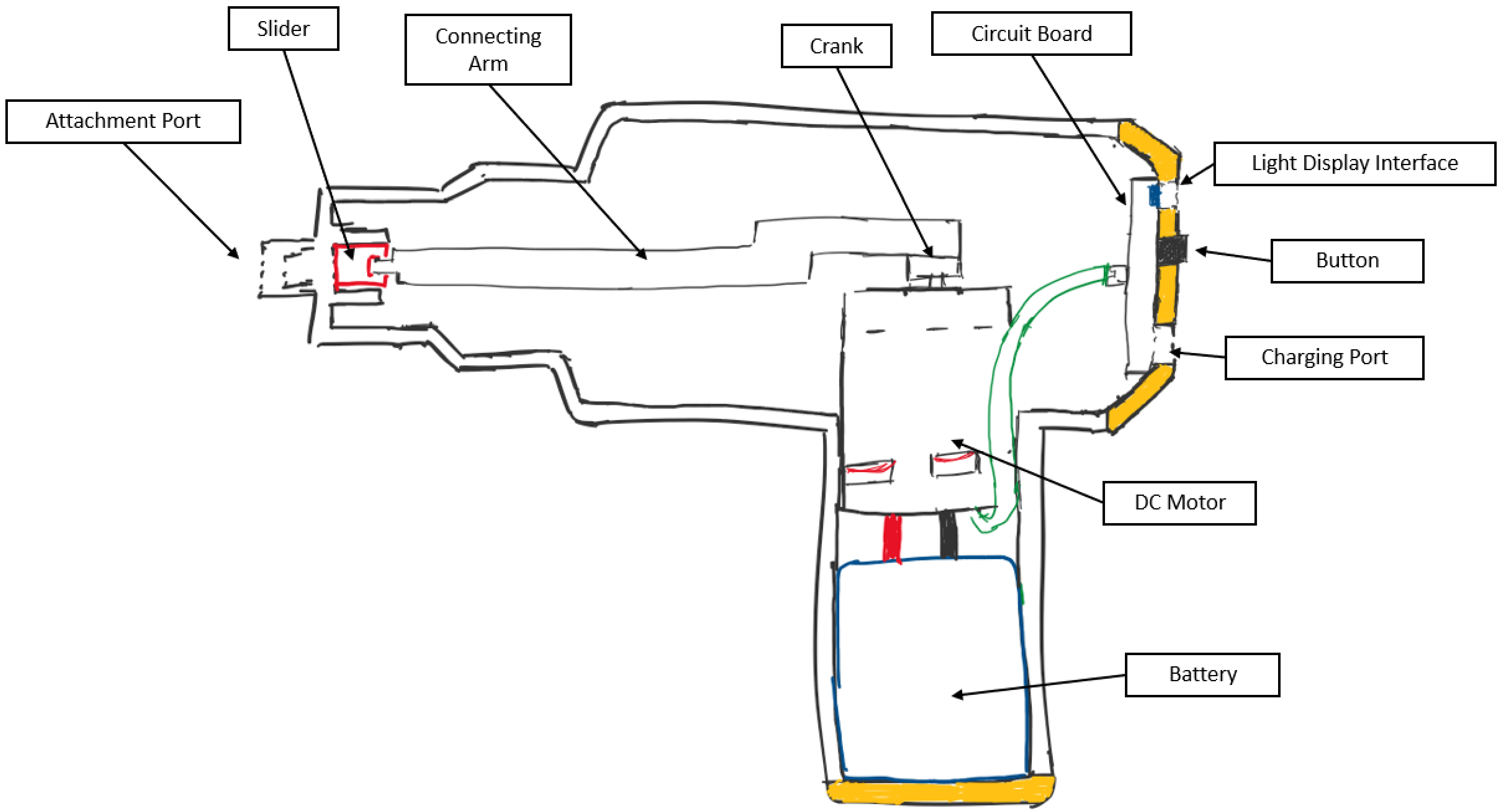
Figure 3. Activity diagram for the massage gun.



Predicted Internal Components

After creating the Blackbox diagram for the massage gun, the next step was to predict what the internal components were of the system. Below is Figure 4, which shows a section view of the massage gun. The different parts of the gun are labeled. Highlights of this figure are that I predicted that the gun uses a slider crank system for the transformation of rotational motion to translational motion because this is a common way of performing this transformation. Also, I predicted that the battery and motor are in the handle which is how it is so compact. The circuit board being in the back is an easy prediction because the light display, button, and charging port are all in that location.

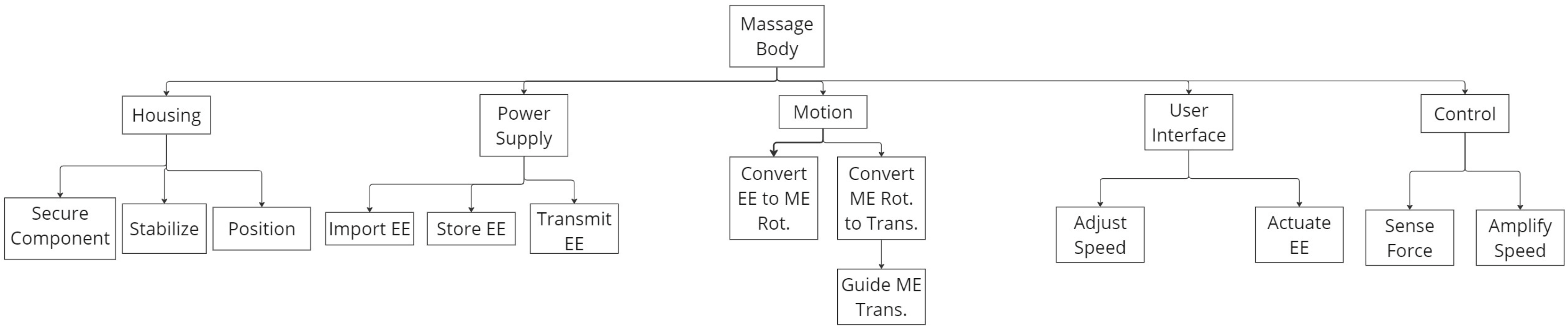
Figure 4. Predicted internal layout of massage gun components.



Predicted Function Tree

After predicting how the internal components of the device would be laid out, a functional tree was created to organize subfunctions that split off from the main function. Figure 5 shows there are five main subsystems for the massage gun. First is the housing subsystem that holds the functions of securing the components of the device, as well as stabilizing and positioning it. The second subsystem is the power supply which imports the electrical energy, stores this energy in the battery, transmits the electrical energy. Motion is the third subsystem which converts the electrical energy into rotational mechanical energy and converts the rotational mechanical energy into translational. From this, the rot. To trans. Function branches to guiding the translational energy. The fourth subsystem is the user interface which adjusts the speed of the motion and actuates the electrical energy. Finally, there is a control subsystem that senses a force when the user presses down on their body and amplifies the speed which is separate from the User Interface (UI) controlled speed increases.

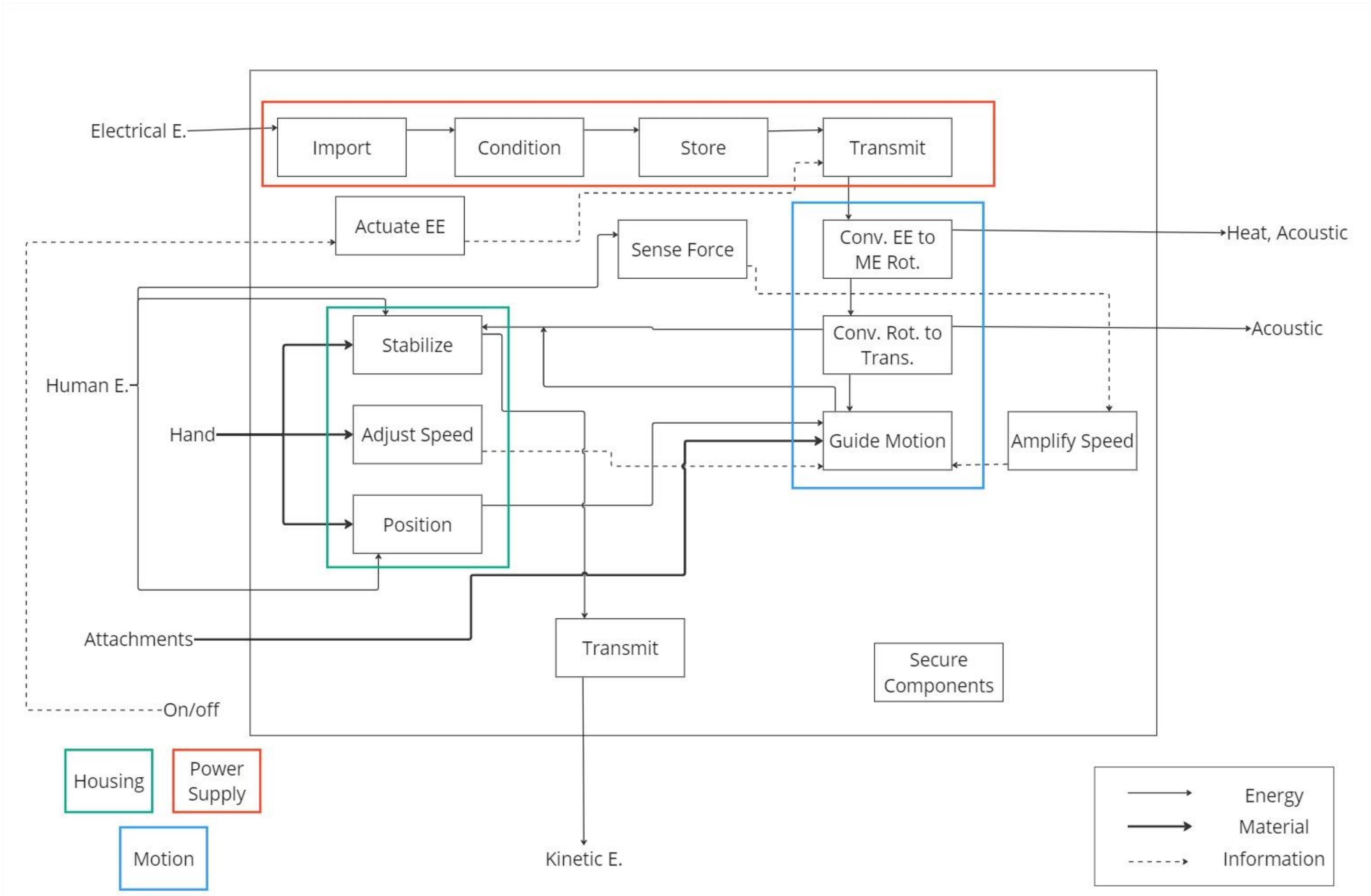
Figure 5. Predicted function tree for the massage gun.



Predicted Function Structure

The final step for this predictive functional modeling is to create a function structure. This diagram is a combination of the fundamental Blackbox diagram with the subfunctions of the function tree integrated inside the box. There are three subsystems that are highlighted with colored boxes. The first group of functions falls under the Power Supply subsystem in red. These are all the same as the function tree with an addition of a conditioning function that allows the voltage from the wall socket to work with the voltage limit for the massage gun. After the electrical energy (EE) flows to the transmit function, the on/off signal when prompted actuates the EE and transmits it to the Convert EE to Mechanical Energy (ME) Rotational then Convert ME Rot to ME Translational. These two functions are derived from the motor and slider crank with the slider then Guiding Motion of the translational energy. The output of these functions are acoustic and heat energies that leave the system. The third subsystem highlighted in the Housing in the green box. The functions in this subsystem all depend on the Hand material which interacts with stabilizing, adjusting the speed, and positioning the device. The stabilizing and positioning also utilizes human energy with the user exerting force to counteract the kinetic energy biproduct from converting rotational to translational energy. The output kinetic energy from the stabilization goes out of the system into the user's arm. The rest of the functions are not grouped due to these functions being supporting/additional to the core subsystems. The on/off signal connects to the actuate EE function which triggers the EE transmit when interacted with. The sense force function comes from the user using human energy to press down on their body, which then amplifies the speed of actuation. Finally, there is a constant function being the housing securing the components of the system.

Figure 6. Predicted function structure for the massage gun.



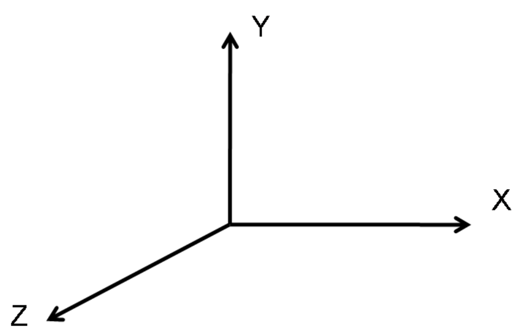
PRODUCT DISSECTION

After the predictive functional modeling, it was time to dissect the massage gun to understand the actual internal workings of the device. This is a necessary step to truly understand the product to create avenues of redesign.

Disassembly Plan

A detailed disassembly plan helps with tracking how each component of the system relates to one another. Below is Figure 7, the coordinate axis I used for the disassembly access directions. The front of the massage gun is pointed in the negative x direction.

Figure 7. Coordinate axis directions.



Below is Table 4, the tabularized disassembly guide. There are eighteen steps needed to disassemble the massage gun. Step 13 is a point of interest in the table. This step required the prying of the base end cap, and I did not have the tools for this. In the attempt to remove it with a screwdriver, I destroyed the component. This highlights an obvious avenue for redesign.

Table 4. Disassembly guide in tabular form.

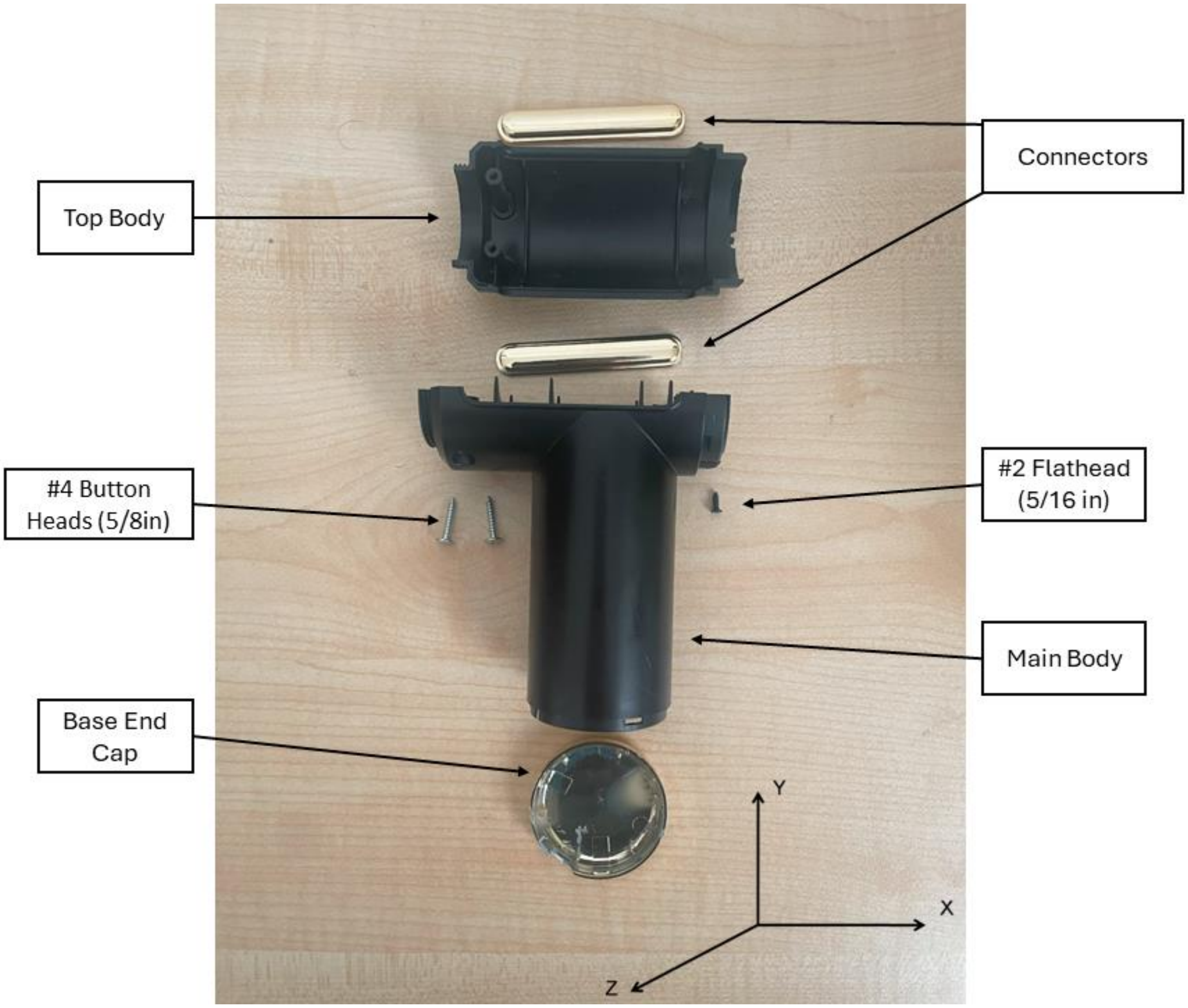
Step	Task	Assembly	Component	Removal Type	Tool(s) Needed	Access Direction
1	Unscrew Main Body (a)	Housing	#4 Button Heads (5/8 in) (x2)	Unscrew	Phillips Screwdriver	-Y
2	Unscrew Main Body (b)	Housing	#2 Flathead (5/16 in) (x1)	Unscrew	Phillips Screwdriver	-Y
3	Remove Back End Cap	Housing	Back End Cap	Pull	Hand	+X
4	Remove Bearing Housing	Motion	Bearing Housing	Pull	Hand	+X
5	Remove connectors	Housing	Connectors	Lift	Hand	+Y
6	Remove Top Body	Housing	Top Body	Lift	Hand	+Y
7	Disconnect Battery from Circuit Board	Power and Control	Lithium Ion Battery, Circuit Board	Pull	Hand	-X
8	Disconnect Motor from Circuit Board	Motion	PMDC Motor, Circuit Board	Pull	Hand	-X
9	Unscrew Slider Crank	Motion	#4 Button Head (5/16 in) (x1)	Unscrew	Phillips Screwdriver	+X
10	Remove Slider Crank	Motion	Slider Crank	Lift	Hand	+Y
11	Unscrew Slider Crank Bearing	Motion	#4 Button Head (7/32 in)	Unscrew	Phillips Screwdriver	+Y
12	Unscrew Motor	Motion	#6 Button Heads (5/16 in) (x2)	Unscrew	Phillips Screwdriver	+Y
13	Remove Base End Cap	Housing	Base End Cap	Pry	Trim Removal Tools	-Y
14	Remove Motor	Motion	PMDC Motor	Pull	Hand	-Y

15	Separate Main Body	Housing	Main Body	Pull	Hand	-Y
16	Unscrew Circuit Board	Power and Control	#1 Button Head Screws (x3)	Unscrew	Phillips Screwdriver	+Y
17	Remove Circuit Board	Power and Control	Circuit Board	Pull	Hand	+Y
18	Remove Button	Power and Control	Button	Pull	Hand	+Y

After documenting how to disassemble the device, I took exploded view pictures of the three different subassemblies that were correctly predicted when doing the predictive functional modeling. Below is Figure 8, showing the housing subassembly. All the parts are disassembled in the positive y direction which is very convenient. There are two main #4 button head screws that fasten all the major housing parts. Also, there is a #2 flathead screw that fastens the back end cap to the main body. The "Connector" parts are a point of interest because I did not realize they were independent of the main body. They are more of a cosmetic feature that does not affect the main function of the housing being to stabilize and position the device.

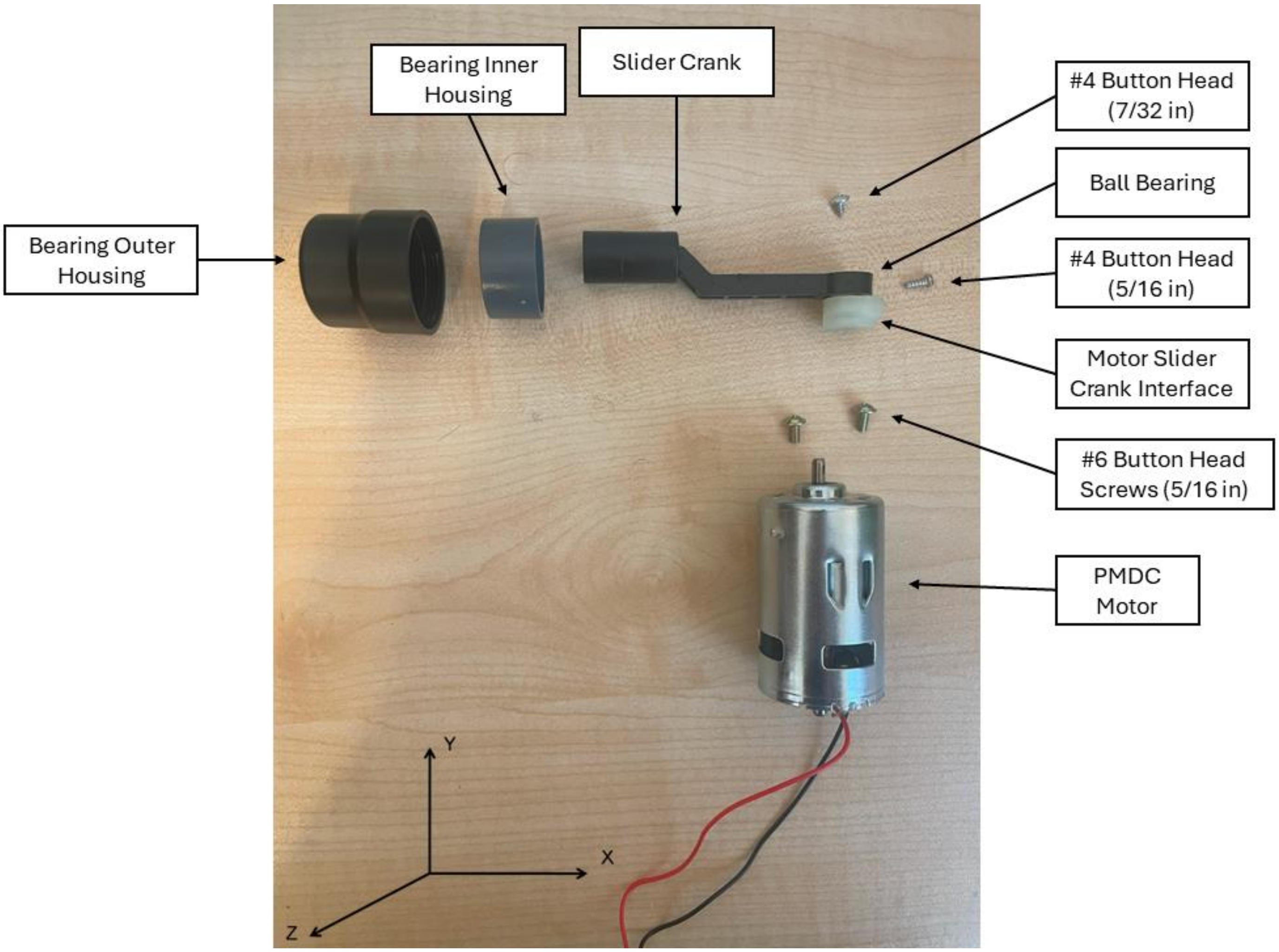
Exploded Views

Figure 8. Housing assembly exploded view.



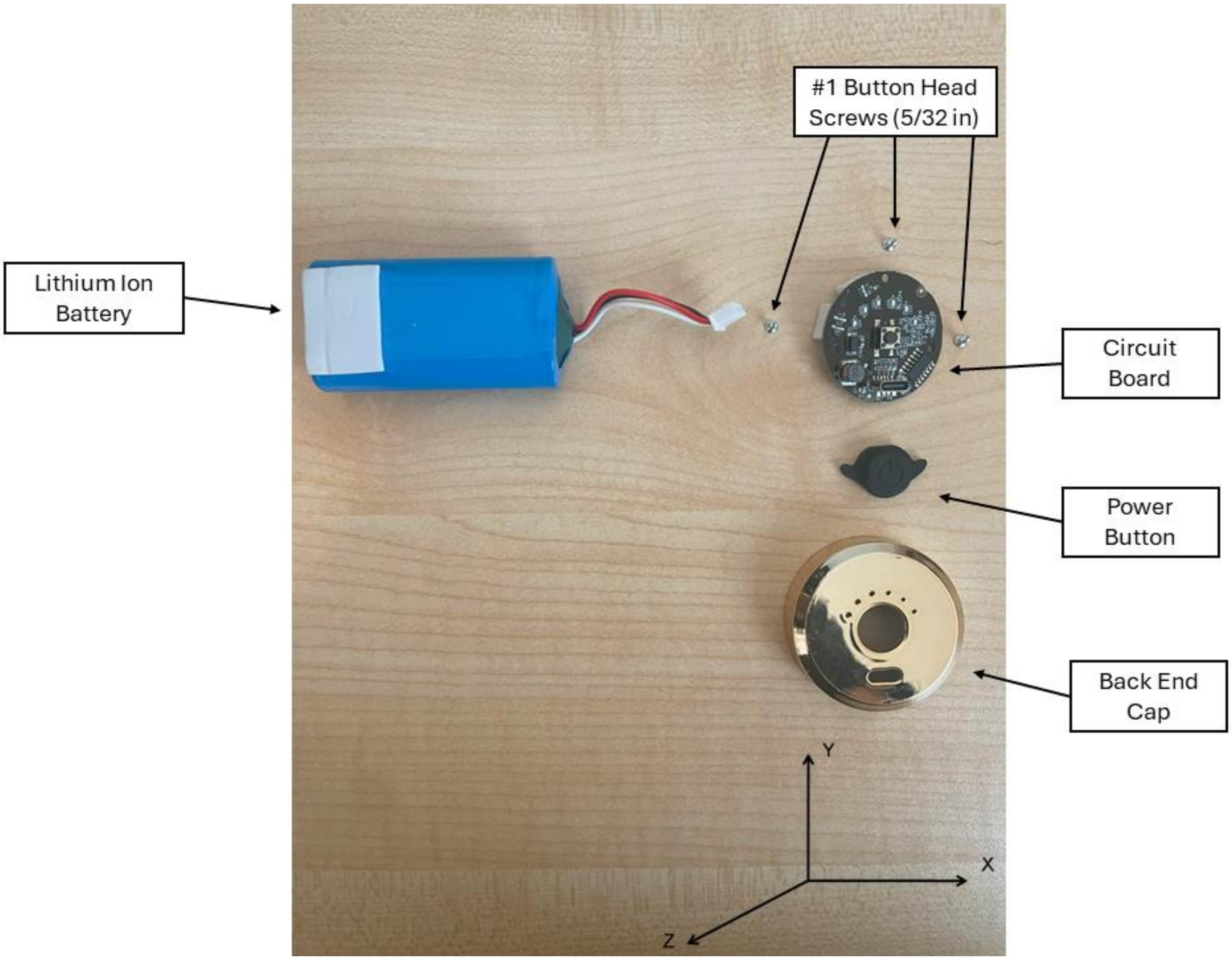
The Motion subassembly is Figure 9 below. It was very interesting taking apart this subassembly because of the bearing outer and inner housings. Essentially, the whole injection molded outer housing holds eight metal balls that the slider crank travels over. I did not expect this feature and rather thought the slider crank would be floating in some way. An issue when disassembling the slider crank was that there is a press fitted ¾ - inch ball bearing inside of it. I attempted to remove this, but it would destroy the slider crank if I had used excessive force. The motor lies parallel to the y-axis which is what I predicted with the component layout.

Figure 9. Motion assembly exploded view.



The last Power and Control subassembly exploded view is below in Figure 10. Here, the battery is positioned parallel to the x-axis which is something I did not predict. It is fixed on top of the slider crank with an adhesive patch which is a crude way of securing it down. This is a major point of redesign. The rest of the components were as expected in this subassembly with the circuit board being connected to the back end cap along with the power button attaching to the board.

Figure 10. Power and control exploded view.



<u>Bill of Materials</u>

The bill of materials for the massage gun was worked on in parallel with the disassembly. Below is Table 5, the tabularized data for the different components and their features. There are twenty different unique components for this device with some duplicate fasteners and two connectors.

The green highlighted cells are the components that belong to the Housing subassembly. All the black and gold parts are assumed to be Acrylonitrile Butadiene

Styrene (ABS) plastic and injection molded. Also, the fasteners are most likely stainless steel because of their color and the commonality of that type of material for these components.

The red highlighted cells are a part of the Power and Control subassembly. The printed circuit board (PCB) is assumed to be FR-4 polyimide, a common material for this type of component. This board has two multipin ports for the motor and battery connection as well as a USB-C port and LED light display. The battery is most likely a lithium-ion battery and has a label informing that is a 7.4 volt, 1200 mAh, 8.88 Wh battery.

Finally, the blue highlighted cells are categorized under the Motion subassembly. This subassembly has the greatest number of parts because of its complexity. The motor is a 755 DC motor, though the actual specifications cannot be found online. Experiments will need to be done to extract the characteristics of this motor. The slider crank, bearing outer housing, and bearing inner housing are all injection molded with ABS.

Table 5. Bill of materials for the massage gun.

Bill of Materials						
Assm. Name	**Part #**	**Qty.**	**Description**	**Material**	**Color**	**Notes**
Housing	1	1	Main Body	ABS Plastic	Black	Injection Molded
	2	1	Back End Cap	ABS Plastic	Gold	Injection Molded, USB-C port and light display holes
	3	2	Connectors	ABS Plastic	Gold	Injection Molded
	4	1	Top Body	ABS Plastic	Black	Injection Molded
	5	1	Base End Cap	ABS Plastic	Gold	Injection Molded

	6	2	#4 Button Head Screw	SS	Silver	5/8-inch length
	7	1	#2 Flathead Screw	SS	Black	5/16-inch length
Power and Control	8	1	Circuit Board	FR-4 Polyimide	Black	Two multipin ports for motor and battery, USB-C port, and light display
	9	3	#1 Button Head Screw	SS	Silver	5/32-inch length
	10	1	Lithium Ion Battery	Lithium Ion	Blue	7.4 V, 1200 mAh, 8.88 Wh
	11	1	Power Button	Rubber	Black	
Motion	12	1	PMDC Motor	Steel	Silver	OEM, 755SLJB-89
	13	1	Slider	ABS Plastic	Black	Injection Molded
	14	1	Bearing Outer Housing	ABS Plastic	Black	Injection Molded
	15	1	Bearing Inner Housing	ABS Plastic	Grey	Injection Molded
	16	2	#6 Button Head Screw	SS	Gold	5/16-inch length
	17	1	#4 Button Head Screw	SS	Silver	5/16-inch length
	18	1	#4 Button Head Screw	SS	Silver	7/32-inch length
	19	1	Ball Bearing	SS	Silver	3/4-inch diameter
	20	1	Crank	Plastic	Yellow	

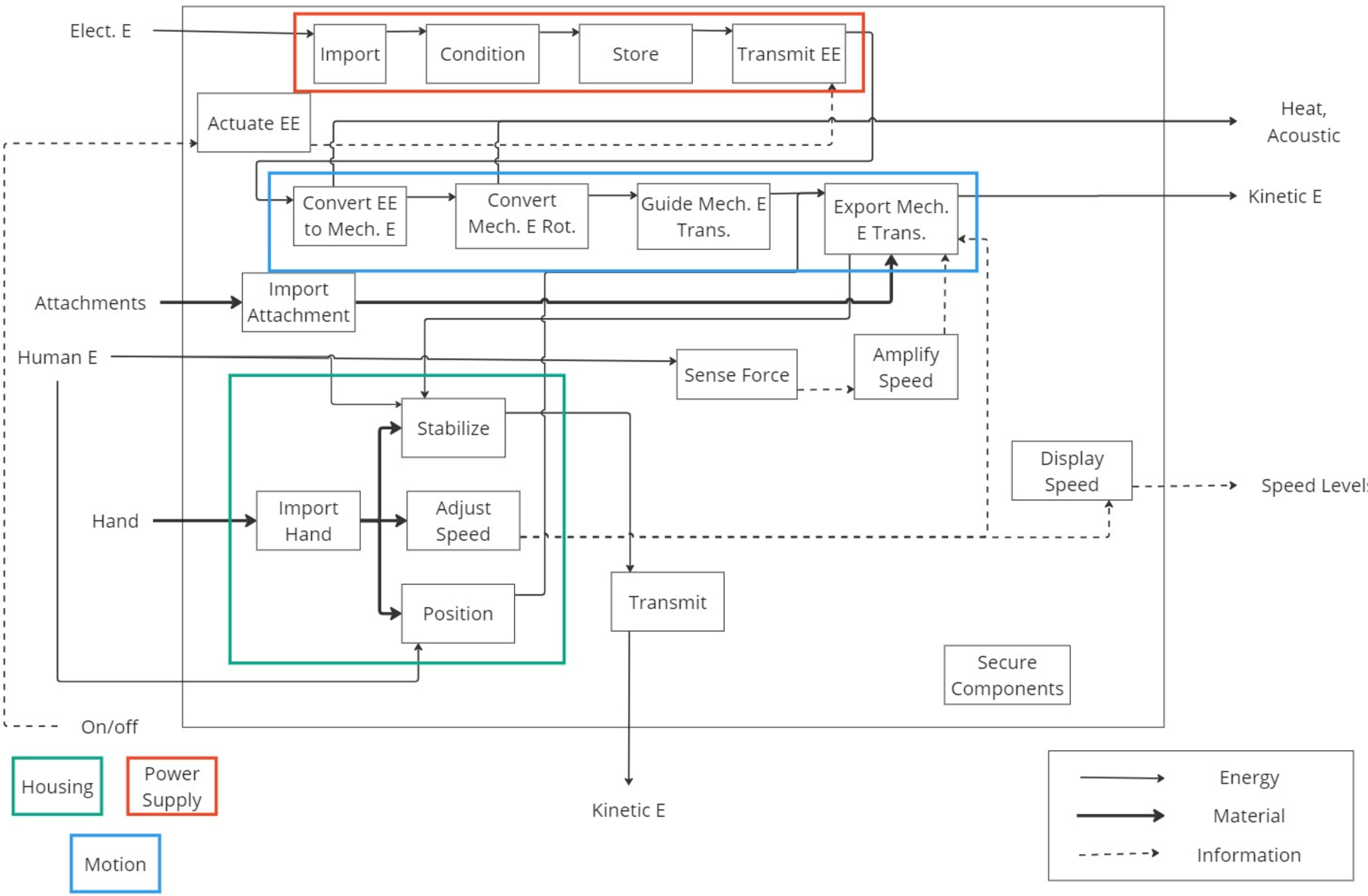
ACTUAL FUNCTIONAL MODELING

After the disassembly of the massage gun, the next step in the process is to go back to the functional modeling of the system to update it with the actual function design. This updated functional model is refined to have a few more functions that exactly describe how the system operates.

Actual Function Structure

Below is Figure 11, the actual function structure of the massage gun after dissecting it. The three main subsystems are still the Housing, Motion, and Power Supply with two main additions being an import hand and export mechanical translational energy. These two functions describe how the hand material is used in the system and how the translational energy is exported out of the system rather than the “guide motion” doing this function. A supporting function for information is displaying the speed. This is done during the normal operation of the massage gun which was overlooked at first. Overall, the function structure did not change much from the predicted one because of my understanding of mechanism design, control design, and careful analysis of the activity diagram and physical use of the massage gun.

Figure 11. Actual function structure of the massage gun.



AVENUES FOR REDESIGN

After all the modeling and dissection, the true design portion begins with Table 6 below. Forty redesign avenues were conceived for the massage gun with the type of redesign being either parametric or adaptive, the technique used to identify these redesigns and the priority of the redesign. Many of the initial ideas used the customer requirements as a reference with the first avenue being to decrease the maximum translational speed of the device with a priority of "must". From index 10 and onwards were more ideas from looking at other massage guns on the market and their features. Indices 29 – 31 were ideated from the disassembly process which were components that are not necessary for the main functions of the massage gun. Indices 32 and onwards were conceptualized by me with interesting features like having neon lights on the inside of the housing to indicate speed level and soothing sounds emitted from the massage gun when operating.

Table 6. Massage gun avenues for redesign.

Index	Redesign Avenues	Description	Type	Technique Used to Identify	Priority
1	Decrease maximum speed	Decrease the maximum translational speed	Parametric	Customer Requirements	Must
2	Add an on/off sticker	A sticker that informs the user how to turn the device on and off	Parametric	Customer Requirements	Nice
3	Increase stroke length	Increase the length the slider cranks travels	Parametric	Customer Requirements	Should

4	Switches with different indicators	Instead of a power button, have a switch that has an on/off function	Adaptive	Customer Requirements	Good
5	Modular	Have all the parts be able to break apart and put back together easily	Adaptive	Customer Requirements	Should
6	Lighter and stronger material	Carbon fiber	Parametric	Customer Needs	Should
7	Hand grip	Rubber or some other high friction material that goes around the handle	Parametric	Customer Needs	Nice
8	Dial for intensity	A physical dial with a knob to adjust massage intensity	Adaptive	Customer Needs	Good
9	Larger range of speeds	A larger range of translational speeds	Parametric	Customer Needs	Nice
10	"Back Scratcher"	A modular back scratcher type attachment that goes on the bottom of the massage gun handle	Adaptive	Customer Needs, Benchmarking	Nice
11	Force impulse when	A vibration pulse from	Adaptive	Customer Needs	Nice

	attachment is inserted	the device to indicate when an attachment is inserted			
12	Touch screen	A more advanced interface that uses a touch screen	Adaptive	Customer Needs, Benchmarking	Good
13	More range of force control	When a person presses down on their body, instead of immediately amplifying the intensity, allow for more range of amplification directly dependent on the force	Parametric	Customer Needs	Nice
14	Larger battery capacity	A different battery with increased mAh	Parametric	Customer Needs, Benchmarking	Nice
15	Damping material around the motor	Make quieter	Parametric	Benchmarking	Nice
16	Triangle handle	An interesting ergonomic grip that uses a triangular shape	Adaptive	Customer Needs, Benchmarking	Nice
17	T-Shaped handle	Another handle form that has two cylindrical	Adaptive	Customer Needs, Benchmarking	Nice

		extrusions above and below the neutral axis of the massage gun			
18	Heated end	A small heater at the end of the massage gun that passes through the attachments to give a soothing warm massage	Adaptive	Benchmarking	Nice
19	Heart shaped handle	A different handle shape that is both ergonomic and aesthetically pleasing	Adaptive	Benchmarking	Nice
20	Collapsible shaft	A foldable front shaft of the massage gun to make it more compact when transporting	Adaptive	Benchmarking	Nice
21	Rotating shaft with two heads	Almost like an electric hand mixer	Adaptive	Benchmarking	Nice
22	Varying stroke lengths during operation	An increase and decrease in stroke length which would vary the penetration depth into a user	Parametric	Customer Needs	Should

23	Pulsing vibrations	Different vibration patterns when operating	Adaptive	Personal	Should
24	Stubby handle	A shorter handle for small handed people	Adaptive	Benchmarking	Nice
25	Trigger	A mechanism to turn on and off the massage gun	Adaptive	Personal	Nice
26	Increase exported force	Increases the force that the user would feel from the device	Parametric	Customer Needs	Good
27	Eliminate “Connectors”	Unnecessary components	Parametric	Disassembly	Nice
28	Eliminate #4 button head screw on crank	An unnecessary component that doesn’t affect the motion of the slider crank	Parametric	Disassembly	Nice
29	Give battery a platform/case to lay on/in	Eliminates the cheap adhesive holding the battery to the slider crank	Adaptive	Disassembly	Should
30	Make base end cap have fasteners instead of snap fit	The base end was destroyed during disassembly because of the tight snap fits, helps to	Adaptive	Disassembly	Should

		make it easier for disassembly			
31	Cleaner soldering and protection of motor wires	To prolong the life of the device if it is transported roughly	Parametric	Disassembly	Should
32	Twisting lock mechanism for back end cap	Instead of a small #2 fastener, have a grooved feature on the end of the main body to twist the back end cap on	Adaptive	Personal	Should
33	Rubber ball attachment	A rubber ball type insert attachment	Adaptive	Personal	Nice
34	Cylindrical battery	A cylindrical battery that can fit on the bottom of the handle	Adaptive	Benchmarking	Should
35	Oil/moisturizer imbued attachment	An attachment that is imbued with oil or moisturizer for additional skin treatment	Adaptive	Personal	Nice
36	Heat sink	A heat sink for the motor to release heat more easily	Adaptive	Personal, Interviewing	Should

37	Neon lights	Neon lights that glow on the inside of the main body for speed indication and aesthetics	Adaptive	Personal	Nice
38	Sounds	Emits soothing sounds like ocean waves when treating physical therapy patients	Adaptive	Personal	Nice
39	Holes for heat control	Perforated top body to allow for heat control from the battery and motor	Adaptive	Personal	Nice
40	Pistol grip	A pistol grip type handle design that increases comfort	Adaptive	Personal	Nice

QUALITY FUNCTION DEPLOYMENT

Quality function deployment is a method to transform customer desires which are usually qualitative to quantitative performance metrics and targets. In the section below, the House of Quality method and diagram was used to capture the relationships between performance metrics and customer needs, identify the correlations between performance metrics, compare qualitatively which competing massage gun is the best, and finally compare the competitors' own performance metrics to the current design to set target values for the redesign process.

House of Quality (HOQ)

Performance Metrics & Correlation Matrix

The main performance metrics found when conducting customer needs analysis are as follows:

- Motor speed (rpm)
- Stroke length (mm)
- Exported force (N)
- Motor torque (N-m)
- Weight (kg)
- Volume (cm^3)
- Batter life (mAh)
- Coefficient of friction
- Speed range (#)
- Price ($)

In the correlation matrix, the performance metrics that have a high positive correlation are:

- Stroke length and exported force
- Stroke length and motor torque
- Weight and volume

All of these are paired because they have the same sign to each respective partner metric. At first glance, weight and volume are two metrics that are desired to be decreased but they both have a negative sign which means they are correlated positively.

Finally in the correlation matrix, the performance metrics that have a high negative correlation are:

- Speed and exported force
- Speed and torque
- Stroke length and volume

These metric pairs’ elements are opposite of each other so one is desired to increase while the other is desired to decrease. These comparisons allow the user to understand how these metrics interact with one another as a reference for future design choices.

Relationship Matrix

In the relationship matrix, the customer needs connect with the performance metrics in the center of the HOQ. The relationship status of each connection is either “strong”, “moderate”, or “weak”. The strongest relationship are as follows:

- Light wight and weight
- Body material quality and yield strength
- Handle size and volume
- Handle grip and coefficient of friction
- Intensity settings and speed range
- Actuation speed and motor speed, exported force, and motor torque
- Battery life and battery life

By quantifying the customer needs with performance metrics, a better understanding of how to redesign the device to serve desired aspects arises. Also, these relationships are directly inserted into the calculations that evaluate a weighted importance value for each performance metric.

Target Values & Technical Difficulty

To set target values for these performance metrics, first research had to be done on some of the massage gun’s competitors. Below is Table 7, which shows the current and competing massage gun performance metrics found on Amazon. Competitor 1 has the best price point, least weight, and least volume compared to the others. Competitor 3 has the best speed range, battery life, and motor speed. Both the current and Competitor 3 massage guns have the best stroke length at 12 mm. And for yield strength, all the devices are made from ABS which is at 315 MPa.

After comparing the devices to one another, target values were set for the redesign. The main targets that are the easiest in a technical sense are the motor speed at 900 rpm, the stroke length at 15mm, and an exported force of 12 N. This exported force is a value found during the parametric redesign phase of the project, which I iterated back to the HOQ target values.

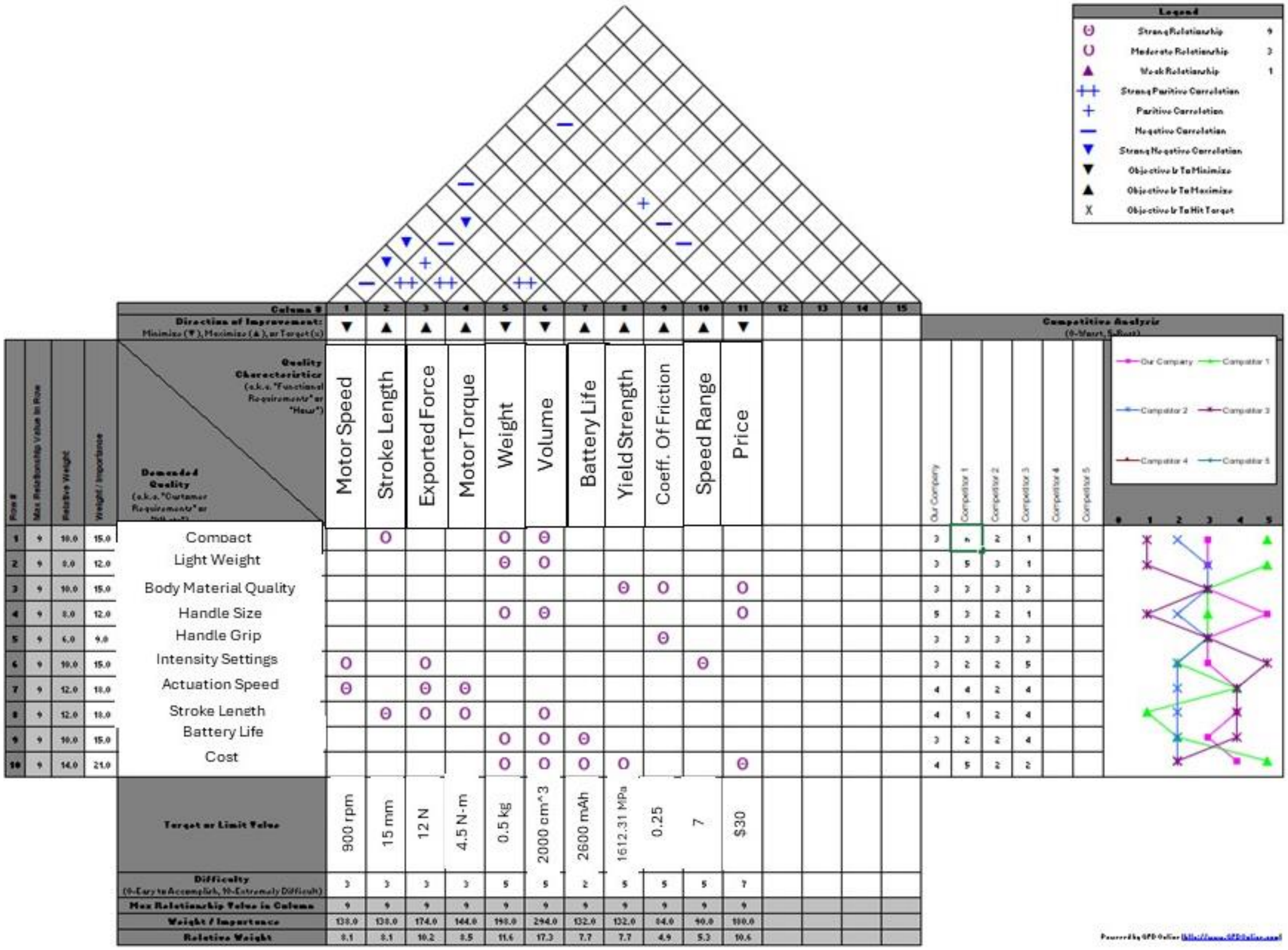
Table 7. Table of the competitive benchmarking between massage guns.

Massage Gun	**Price ($)**	**Mass (kg)**	**Volume (cm^3)**	**Speed Range (#)**	**Battery Life (mAh)**	**Speed (rpm)**	**Stroke Length (mm)**	**Yield Strength (MPa)**
Current	30	0.635	2064.77	6	1800	3200	12	315
Competitor 1	22	0.358	944.525	5	1500	3200	N/A (Worst)	315
Competitor 2	60	0.750	3065.77	5	1500	2800	8	315
Competitor 3	60	1.36	4436.80	7	2000	3300	12	315

House of Quality Results

After entering all the values, relationships, correlations, and technical difficulties, weights of importance were calculated. Volume has the most weight importance with mass trailing behind it. This is logical because the geometric properties of a product are the base of many other metrics. If a solution is too large for the bounding box of the target volume value, then that solution needs to be adjusted to accommodate to the volume requirement. Also, an ideal solution might be too heavy and needs to be reevaluated. Price and exported force are the next two metrics that are important. Many other metrics are dependent on price, two being the type of material and how much material a solution desires. Finally, though, the exported force is the main metric I am trying to improve, yet volume, mass, and price take priority in this analysis which is interesting. This goes to show that the constraints of geometry and cost outweigh a solution that might seem the best but is large, heavy, and costly.

Figure 12. House of Quality for the massage gun.



ADAPTIVE REDESIGN

This is the start of the redesign process for this project. Adaptive redesign involves changing or adding subfunctions/features to the product. From the customer needs analysis, the “intuitive interface” was the second most important need. This need is broad enough to allow for creative concepts which is why I focused on it. The following sections will explain the different techniques used such as C-Sketch, Mind Map, Morphological Matrix, and finally some sketched concepts. Following this, the next section will explain the concept selection phase which utilized methods such as Back of Envelope Calculations (BOEs) and Pugh Chart to deliver a final concept.

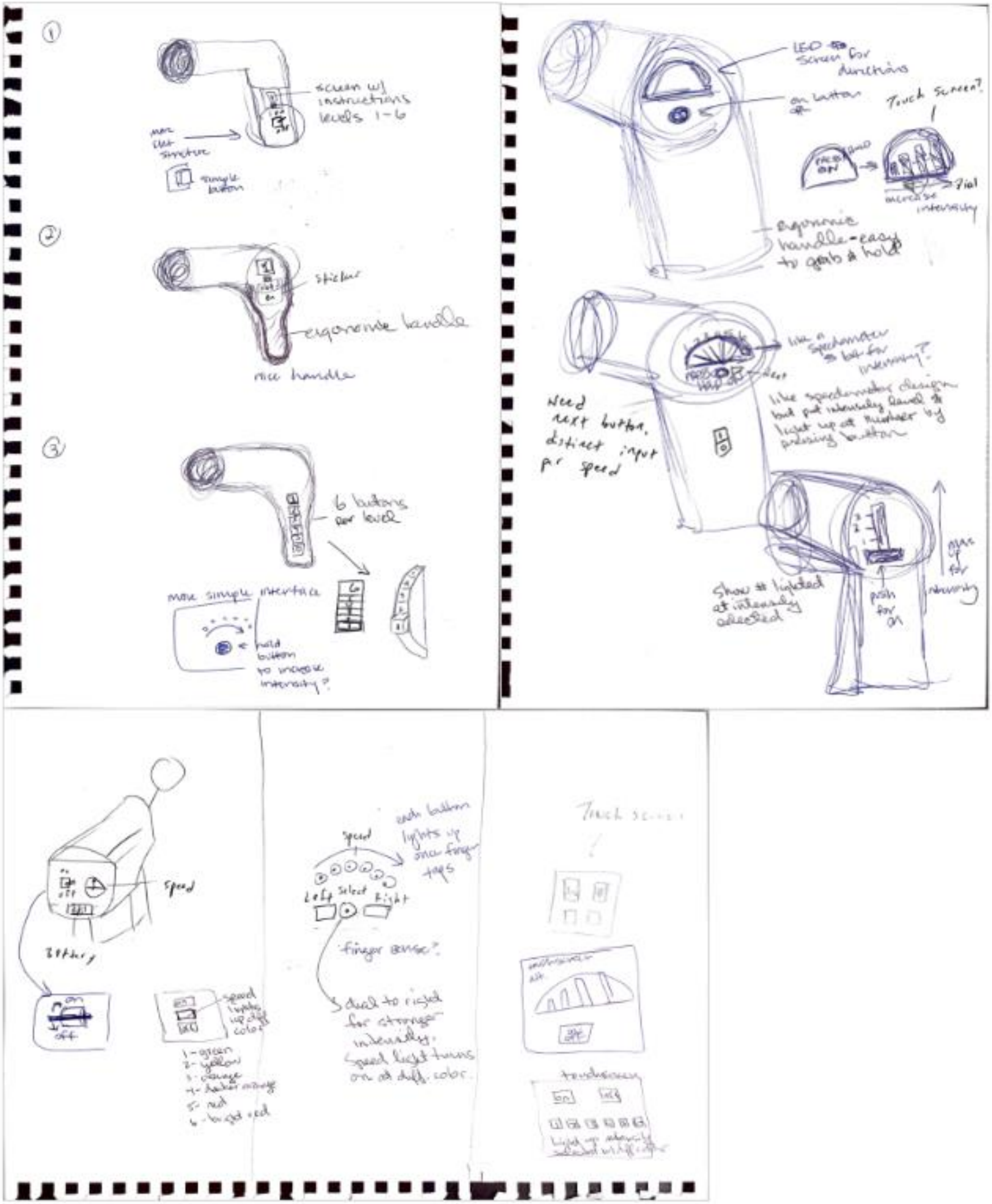
Concept Generation

Conceptualizing ideas is a key element of the design process. This stage can be a base point for iteration because if a concept does not pan out further down the design path, then more ideas need to be explored. In the next section will show the techniques that used for redesigning the massage gun.

6-3-5/C-Sketch

The first step I took for concept generation was conducting a 6-3-5 or C-Sketch. This technique is used to generate multiple different concepts in a group of people. By sketching three ideas on a piece of paper, this page is then rotated about a circle of people several times depending on how many participants there are. The process was smooth with the people I performed the exercise with. I asked my girlfriend, a fashion major at UT, and her mother, a middle-aged woman who focuses on interior design. Both are design oriented, so the solutions they came up with for an improved user interface were valuable. I taught them the technique by explaining it multiple times and using gestures to show how the passing of papers worked. Most of the ideas they came up with were standard to what is out on the market for these massage guns. In the end, the ideas they came up with helped solidify my own ideas such as an LED screen, stickers, or engravings for speed option visualization and a dial or slider for adjusting the speeds. Below is Figure 13, which shows the three different papers used for the technique.

Figure 13. Image of the 6-3-5/C-Sketch



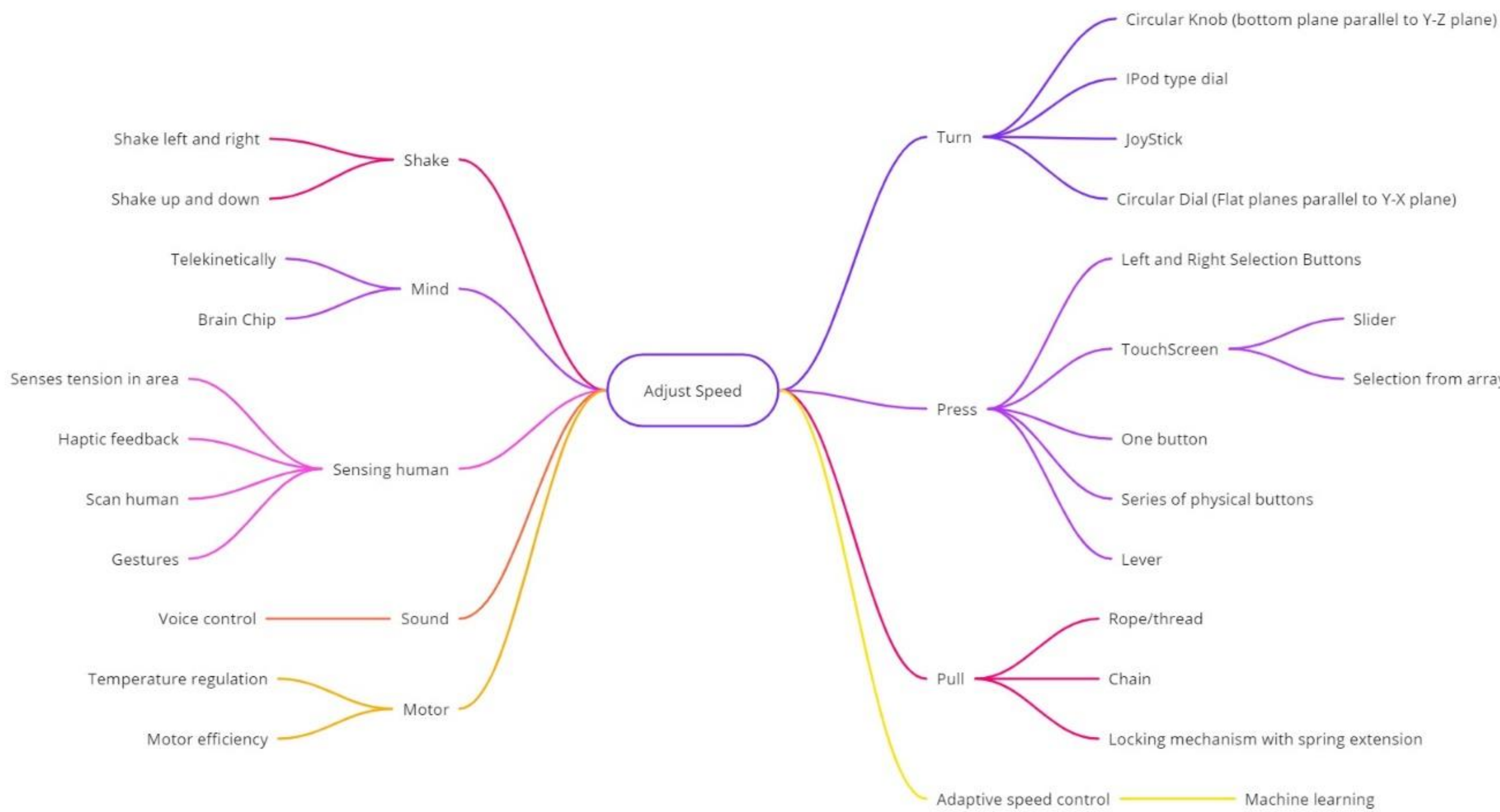
Mind Map

Another technique I utilized was the mind map method. For this, the center node of the graph is the main function that is then branched into multiple other nodes. This is a somewhat chaotic method because it is ideal for the user to do this fast with quantity being better than quality. For my mind map in Figure 14 below, there are nine different main branches that split off into individual solutions. These branches are:

- Shake
- Mind
- Sensing human
- Sound
- Motor
- Turn
- Press
- Pull
- Adaptive speed control

The “turn” and “press” branches are the most realistic and are directly applied to the morphological matrices used later in the design process. As a side note, I used a large language model (LLM) i.e. ChatGPT to generate some of the ideas for this mind map. I learned of this technique from Dr. Wood who was a guest speaker during the semester this project took place. Using LLMs for this sort of task is useful because they can give you many ideas in seconds which might have taken a human much longer to ideate.

Figure 14. Image of the mind map graph for the adjust speed function.



Morphological Matrix

The next step in the concept generation path was using morphological matrices. These matrices are tables used to focus on certain aspects from the idea generation results. These tables organize the ideas which allow the user to select different elements to combine into unique concepts.

Below is Table 8, the morph matrix used for the massage gun. The different ideas are split into categories found from the customer needs analysis. Subfunctions from the functional modeling previously done on the device are paired under their respective category. To the right of the subfunctions are the current and other solutions. These other solutions were found from benchmarking and the idea generation results for adjust and display motor speeds. Some of the different materials are polylactic acid (PLA) which is used in FDM printing and is biodegradable, polyethylene terephthalate glycol (PETG) which is also used in FDM printing, yet it is more ductile than PLA. These materials were selected because they are the most accessible to UT students from the Texas Invention Works workshop.

Something to point out is the lack of solution quantity for the storing electrical energy (EE) and actuate EE subfunctions only having two solutions. This was due to keeping the ideas grounded to reality rather than having solutions like shaking the massage gun to turn it on.

There were four concepts derived from different combinations of solutions from the base morph matrix. These matrices with selected solutions are in Appendix A.

Table 8. Morphological matrix table for the massage gun.

Category	Subfunction	Current Solution	Other Solutions		
Motion	Convert EE to Mech E Rot	PMDC Motor	Brushless DC Motor	Stepper	Servo
	Convert Mech E Rot to Trans	Slider Crank	Linear Actuator	Rack and Pinion	
Ergonomics	Import Hand	Cylindrical	Pistol Grip	Deformable Grip	Abrasive Grip
	Position	Hand	Hooked Extension	Stick	
	Stabilize	ABS	Carbon Fiber	PLA	PETG
Speed Control	Adjust Speed	Button	Multiple Buttons Dial	Slider	Touchscreen
	Display Speed	LED Lights	LED Screen Stickers	Touchscreen	Engraved
Power Supply	Import EE	USB C	Directly from Outlet Cord	Hand Crank Generator Port	Solar Panel Port
	Store EE	LiPo Battery	Alkaline Battery		
Controls	Actuate EE	Button	Switch		
	Sense Force	Current Feedback	FSR	Mini Scale	

Concepts for the Massage Gun

Four concepts emerged from mixing and matching different solutions together from the base morph matrix (Appendix A). Below are Solutions 2 through 4 with the first shown as the final concept.

Figure 15 is the sketch of Solution 2: PETG deformable grip. The main features of this concept are the brushless DC motor, alkaline batteries, and rack and pinon for the motion and power supply. This concept also integrates an LED screen and multiple buttons for speed display and adjustment. The hooked extension is a feature found when researching other massage guns. This essentially works as a backscratcher type device which allows for the massage gun to reach more of the body when only one person uses it.

Figure 16 is Solution 3: carbon fiber pistol grip. The pistol grip idea is thought to be more ergonomic when using the massage gun for long periods of time because the hand can rest on the back lip of the grip, another point of contact that distributes the vibrations better.

Figure 17 is the sketch of Solution 4: PLA stick extension. This stick extension is like the hooked extension but is a straight rod instead of curved.

Figure 15. Massage gun Solution 2: PETG deformable grip concept.

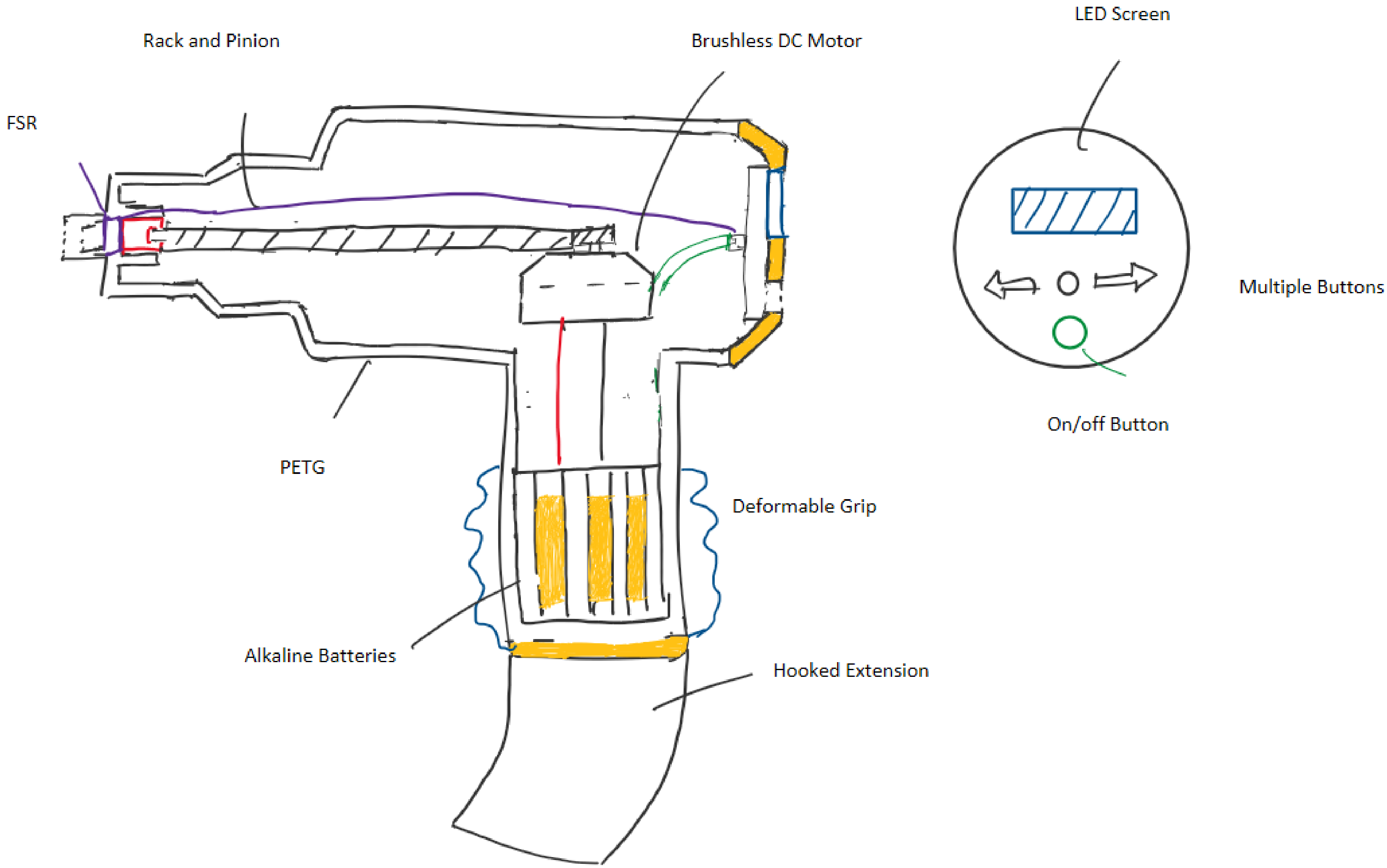


Figure 16. Massage gun Solution 3: carbon fiber pistol grip concept.

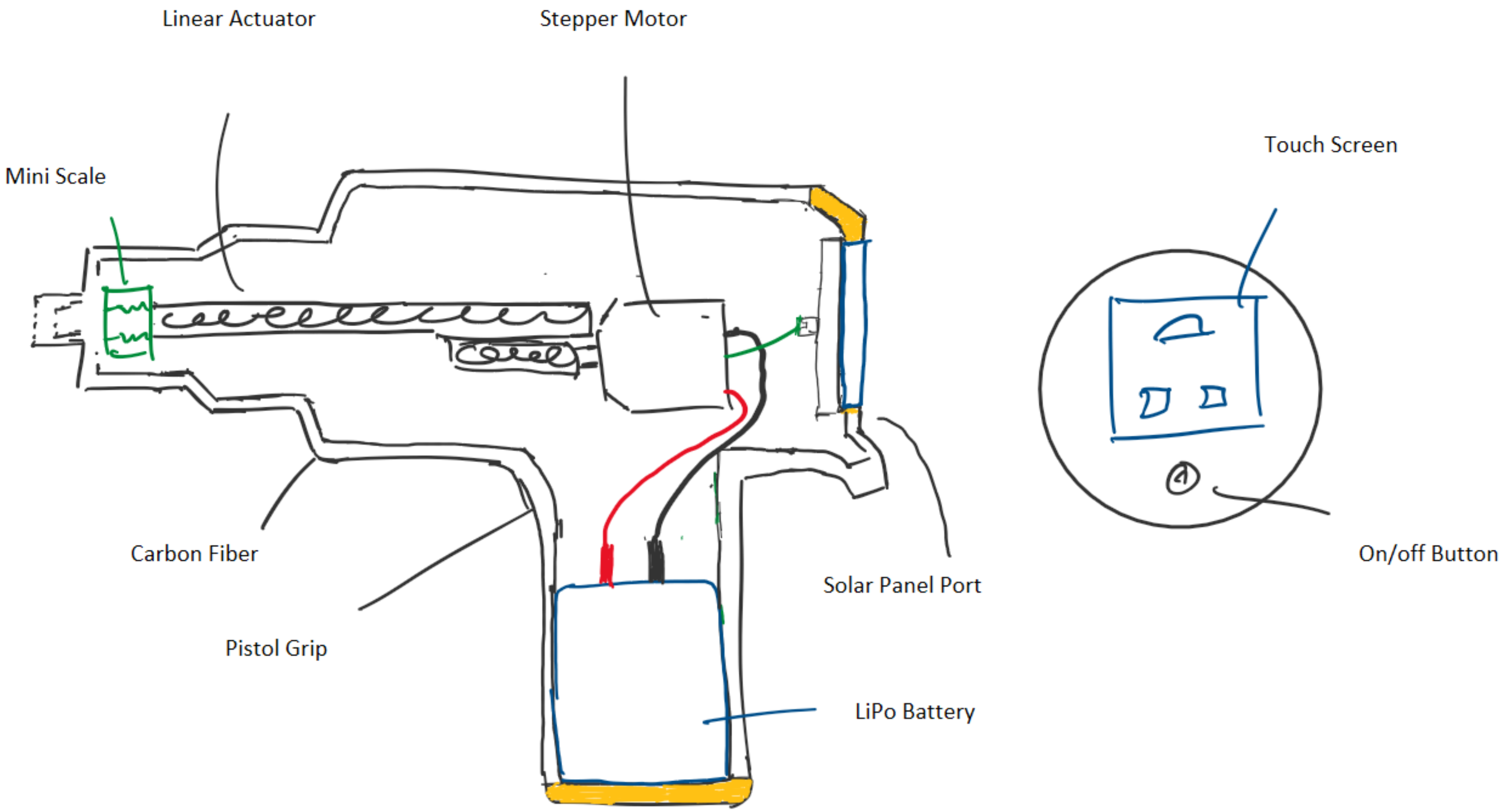
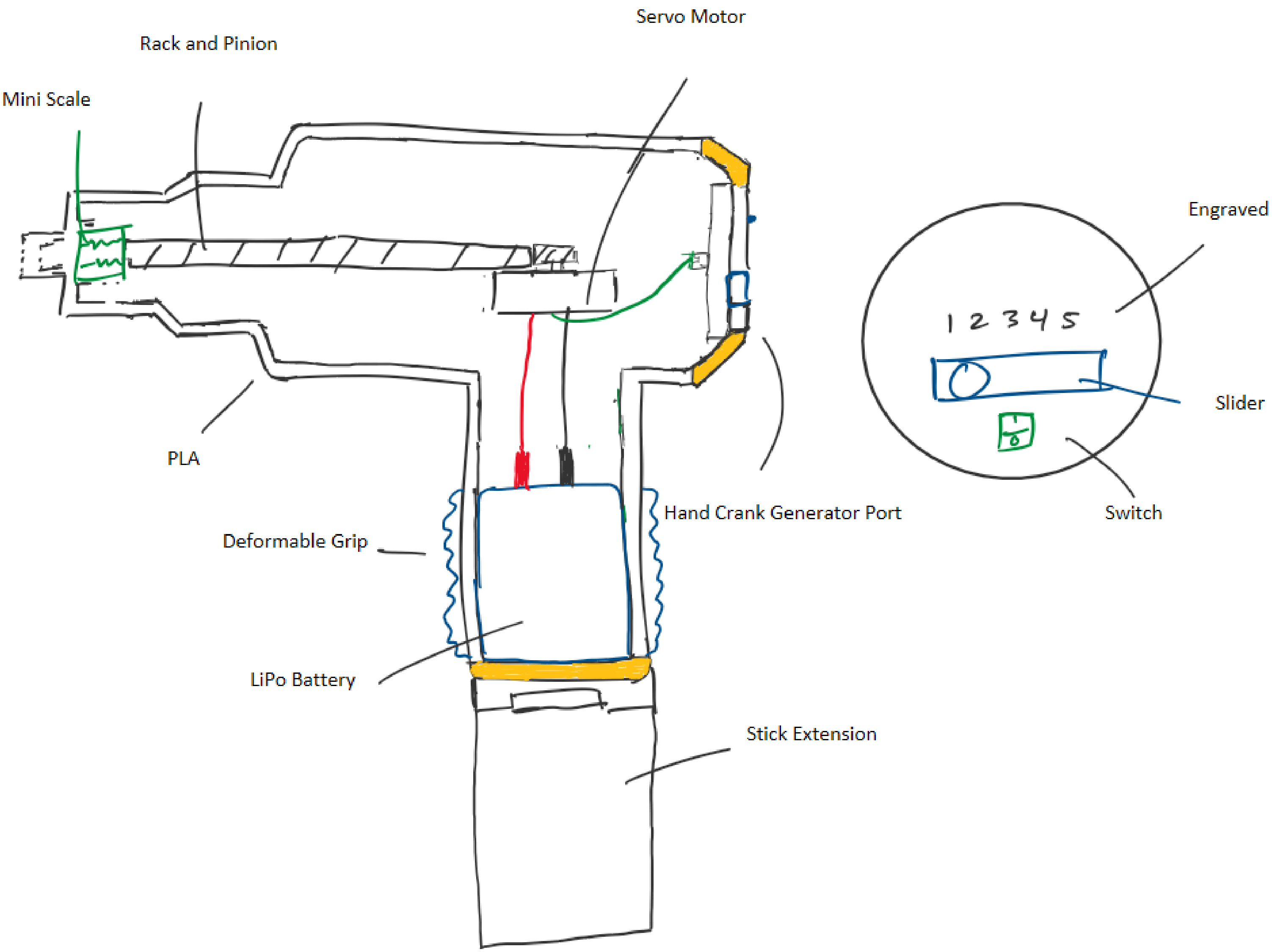


Figure 17. Massage gun Solution 4: PLA stick extension concept.



Concept Selection

The Pugh Chart method was used after the concept generation phase. A Pugh chart systematically evaluates each concept's performance metrics to a datum being the current design. Back of Envelope calculations were done to receive quantitative results to compare the concepts to each other. The sections below explain this in more detail.

Back of Envelope Calculations

Back of Envelope calculations (BOEs) are a simple way of testing different concepts' performance metrics to deem which is "better or worse" to the datum. Appendix B shows the calculations by using MATLAB.

Pugh Chart

Table 9 below shows the Pugh chart created for the massage gun concepts with the current design as the datum. Solutions 1 and 3 are on par with the current design when comparing the performance metrics from the BOEs. An issue with Solution 1 though is that it will weigh more than the current design. Solution 2 is the worst with -4 as its score. It weighs more with the hook extension, and it has a worse force and speed output due to its brushless DC motor and rack and pinion. Also, the coefficient of friction for PETG is lower than ABS.

Ultimately, Solution 1 was chosen because it was on par with the current design and is the most realistic to implement.

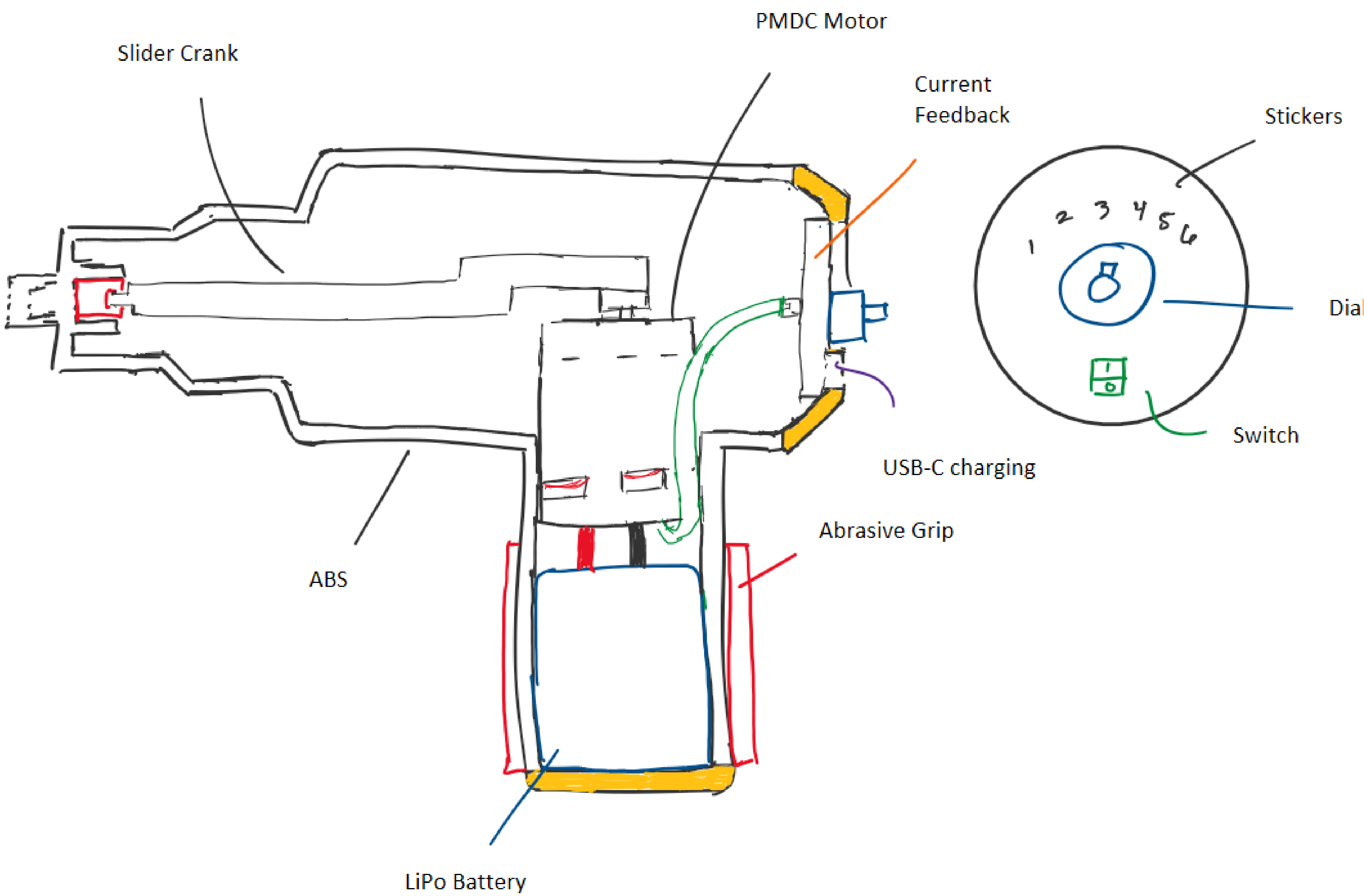
Table 9. Pugh chart with the current design as the datum.

Datum: Current	Criteria	Current	Solution 1	Solution 2	Solution 3	Solution 4
	Weight	0	-	-	-	-
	Output Force	0	0	-	+	-
	Motor Speed	0	0	-	-	-
	Yield Strength	0	0	+	+	-
	Coefficient of Friction	0	+	-	+	+
	Motor Torque	0	0	-	-	+
	Sum of +	0	1	1	3	2
	Sum of -	0	-1	-5	3	-4
	Sum	**0**	**0**	**-4**	**0**	**-2**

Final Concept

Below in Figure 18 is the sketch of Solution 1, the Final Concept. This utilizes many of the current design features because this is the most realistic solution such as the PMDC motor, crank slider, and LiPo battery for power and motion. The dial, stickers, and switch are the changes to the user interface, and the abrasive grip is the change to the ergonomics.

Figure 18. Image of the final massage gun concept.



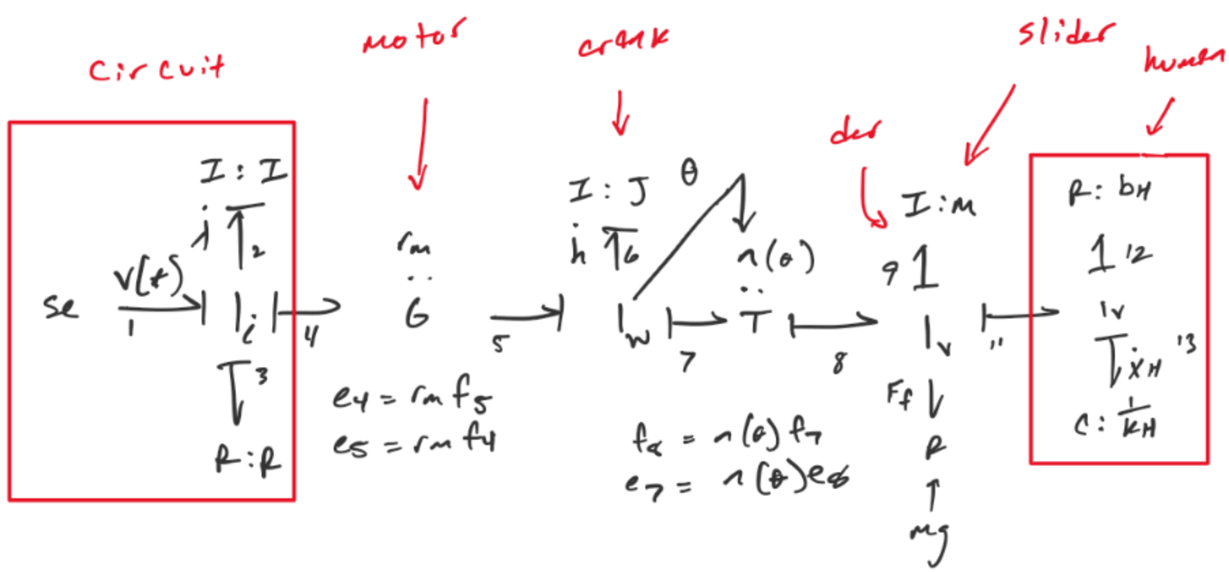
PARAMETRIC REDESIGN

For this parametric redesign, I decided to analyze the output force and displacement of the massage gun on a human's body. To model this concept, I utilized bond graph methods to collect the state equations and visualize the transient and frequency responses.

Bond Graph

Below is Figure 19, the mathematical model represented as a bond graph. This model consists of 5 elements being the circuit for the DC motor, the motor itself, the crank, the slider, and finally the human. This is a third order system with inertance in the circuit and crank, and a capacitance in the human. The slider's inertance is in derivative causality because it is dependent upon the flow of the crank, so it is not an independent state variable. The crank-slider mechanism is a special kind of transformer called a *modulated transformer* which is dependent on the integral of the flow before it. Also, I added Coulomb friction upon the slider as it translates through the orifice of the massage gun. These two additions make the system nonlinear which results in more complicated behavior.

Figure 19. Image of the bond graph for the massage gun.



States and State Equations

Now, to find the state equations, first I needed to define the state variables for this system. Below, Equation 2 shows the three state variables being the flux linkage of the circuit, the rotational momentum of the crank, the displacement of the human's skin. The last variable is the modulation variable, θ for the crank-slider.

$$\overline{x} = \begin{bmatrix} \lambda \\ h \\ x_H \\ \theta \end{bmatrix} \tag{2}$$

The force due to the dry friction between the slider and the orifice is in Equation 3 below. Here, translational velocity is the conversion from rotational via the transformer modulus.

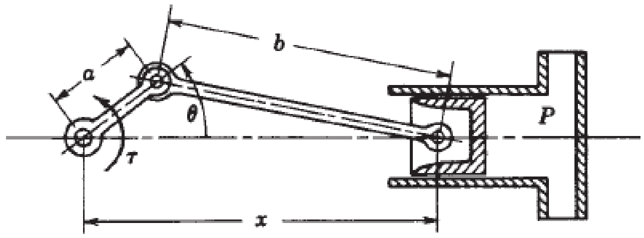
$$F_f = \mu mg[sgn(\frac{n(\theta)}{J}h)] \tag{3}$$

This modulus is described below in Equation 4, which was found in Karnopp's System Dynamics Modeling, Simulation, and Control of Mechatronic Systems (2012). This is a standard modulus equation for a crank-slider.

$$n(\theta) = -a\sin(\theta) - (b^2 - a^2\sin^2(\theta))^{-1/2}a^2\sin(\theta)\cos(\theta) \tag{4}$$

The variable a is the length of the crank and b is the length of the slider which is visually described below in Figure 20.

Figure 20. Image of a crank-slider (Karnopp, 2012).



(a)

After establishing the transformer modulus, I began to derive the state equations. Below, Equations 5 – 8 are the key equations that describe the behavior of the system.

$$\dot{\lambda} = \frac{-R}{I}\lambda - \frac{r_m}{J}h + V(t) \tag{5}$$

$$\dot{h} = \left[1 + \frac{mn^2(\theta)}{J}]^{-1}\right] \left[\frac{r_m}{I}\lambda - n(\theta)\mu mg\left(sgn\left(\frac{n(\theta)}{J}h\right)\right) - \frac{n^2(\theta)b_H}{J}h - n(\theta)k_H x_H)\right] \tag{6}$$

$$\dot{x_H} = \frac{n(\theta)}{J}h \tag{7}$$

$$\dot{\theta} = \frac{1}{J}h \tag{8}$$

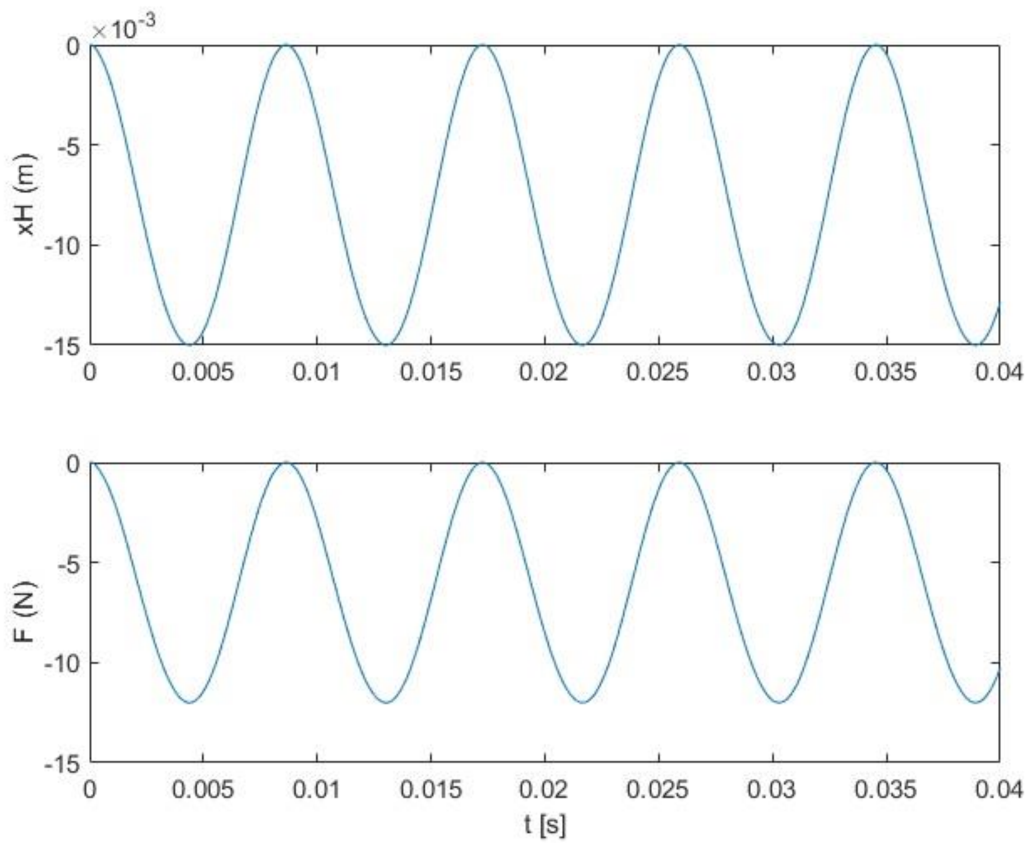
Where $r_m = 16.4e^{-3}\ Nm/A$ and is the motor torque modulus, $a = 7.5e^{-3}\ m$ and is the length of the crank, $b = 90e^{-3}\ m$ and is the length of the slider, $I = 0.02e^{-3}\ L$ and is the inductance of the motor, $R = 0.117\ A$ and is the resistance of the motor, $m_{SC} = 0.005\ kg$ and is the mass of the crank, $J = \frac{1}{2}m_{SC}\left(\frac{a}{2}\right)^2 = 3.52e^{-8}kg - m^2$ and is the mass moment of inertia of the crank, $m = 0.0482\ kg$ and is the mass of both the slider and the attachment, $\mu = 0.2$ and is the coefficient of the friction for ABS of ABS, $V_0 = 12\ V$ and is the nominal voltage of the motor, $k_H = 800\ N/m$ and is the compliance of human skin, and finally, $b_H = 0.845\ Ns/m$, which is the damping of human skin.

I utilized the Maxon RE040 motor's specifications because they were the most descriptive when looking for a torque constant and it is similar enough to the DC motor the massage gun uses. The other values were found by measuring and weighing the crank-slider.

Transient Analysis/Time-Domain

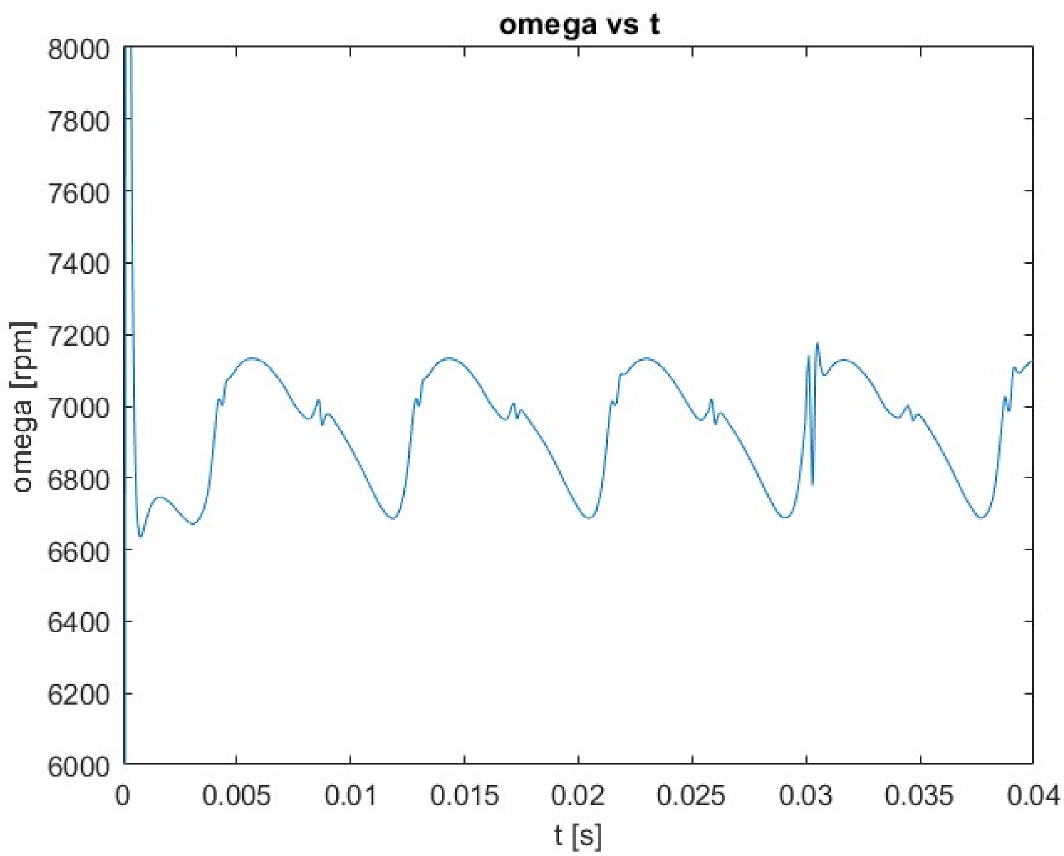
True analysis began after deriving these equations. Below is Figure 21, which shows the stroke length of the slider and the force output into the human. Here, it is seen that amplitude of the slider translational movement is 15 mm. A very interesting phenomena occurred where the length of the crank is exactly ½ of the stroke length. This is the target value set for the stroke length so by manufacturing a crank that is 2.5 mm greater than its current length of 5 mm will achieve this target. And due to this increase in stroke depth, the force will also increase because it is directly proportional.

Figure 21. Stroke length of the crank-slider and the force output into the human.



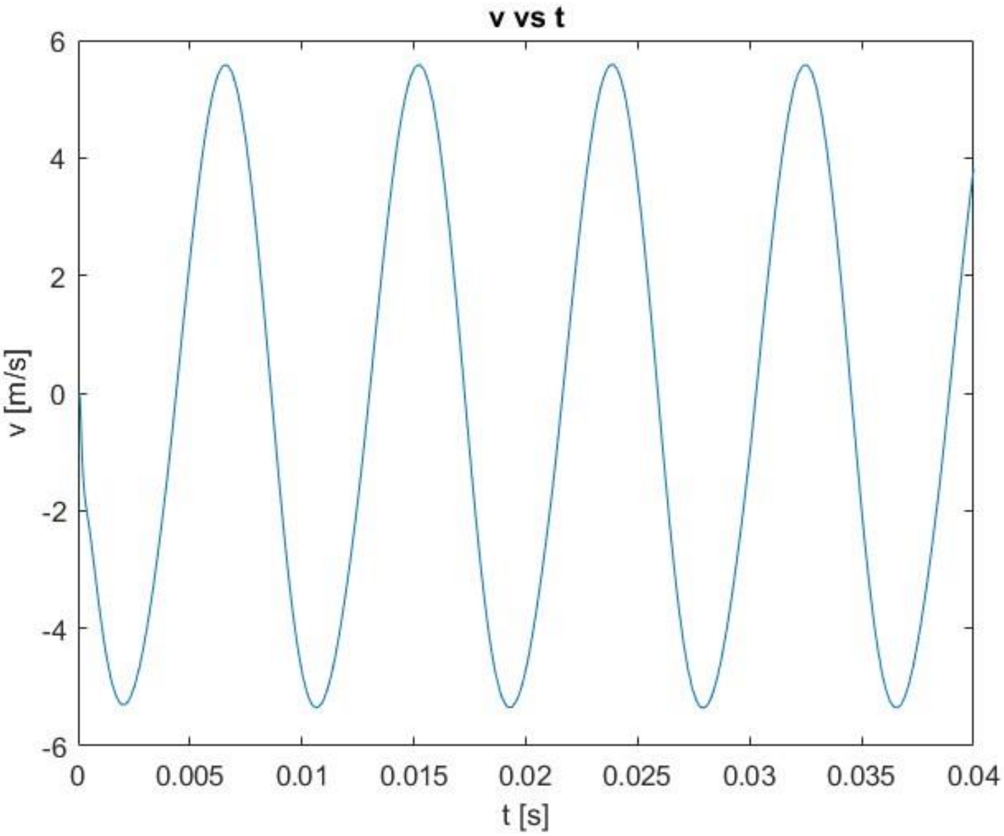
Next, I looked at the rotational velocity of the system and with the motor output spinning around 7000 rpm. Figure 22 below shows this behavior. The spike in this figure around 0.03 seconds is due to the damping from the human. When experimenting with the equations, this term influences the transient response. When the time span is lengthened, about every four cycles is when the spike appears.

Figure 22. Plot of the rotational speed of the system.



And finally, the last behavior analyze for the transient response is the translational velocity. Below is Figure 23 which shows the maximum amplitude being around 5 m/s for the slider.

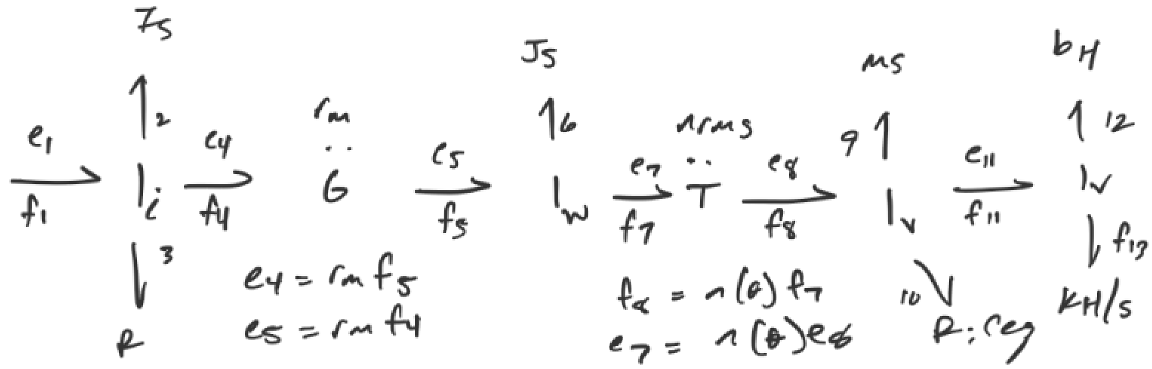
Figure 23. Translational velocity versus time of the slider.



Impedance Methods/S-Domain

Now, after analyzing the system in the time domain, the next step was to go into the frequency domain. Below is Figure 24, the impedance bond graph for this system. Something to point out is that both the transformer modulated modulus and the dry friction are nonlinear equations. This is not ideal when using impedance methods to derive a transfer function and so these two needed to be linearized.

Figure 24. Image of the impedance bond graph.



With the modulated transformer modulus being oscillatory, a Root Mean Square value was found to make it a constant value. This came out to be 0.0042.

To begin this linearization of the Coulomb friction to find an equivalent damping coefficient c_{eq}, first the amplitude of the force input into the slider needed to be found (Inman, 2014). Below is Equation 9 which shows how the nominal input voltage is related to the output force into the slider.

$$F_0 = \frac{r_m}{n_{rms}}\left(\frac{V_0}{R}\right) \tag{9}$$

After finding this value, the inequality below in Equation 10 needed to be true to find the equivalent damping. One could find ideal values for either the coefficient of friction or the mass of the slider, though, the force on the right side of the inequality is much greater than the frictional force, so changes to the slider are not needed.

$$4\mu mg < \pi F_0 \tag{10}$$

Because the inequality above is true, an equivalent damping ratio was found with Equation 12 below. The frequency of the system was found through using the period of the displacement versus time function which was around 117 Hertz.

$$c_{\mathrm{eq}} = \frac{4\mu mg}{\pi\omega X} \tag{11}$$

After collecting the linearized coefficients, a linear multiplication throughout the system was done seen in Equation 12 below. This technique is used to find the desired transfer function, in this situation it is flow 13 over effort 1, or the displacement into the human over the input voltage.

$$\frac{f_{13}}{e_1} = \left[\frac{f_8}{f_7}\right]\left[\frac{f_5}{e_5}\right]\left[\frac{e_5}{f_4}\right]\left[\frac{f_4}{e_1}\right] \tag{12}$$

Below is Equation 13, the derived symbolic transfer function for this system.

$$G(s) = \frac{nr_m s}{(Imn^2 + IJ)s^3 + (JR + Ib_H n^2 + Ic_{eq} n^2 + Rmn^2)s^2 + (r_m^2 + Ik_H n^2 + Rb_H n^2 + Rc_{eq} n^2)s + Rk_H n^2} \tag{13}$$

Equation 14 below shows the substitution of the actual values in Equation 13. This system acts almost like a 1st order one due to how small the first and second coefficients are.

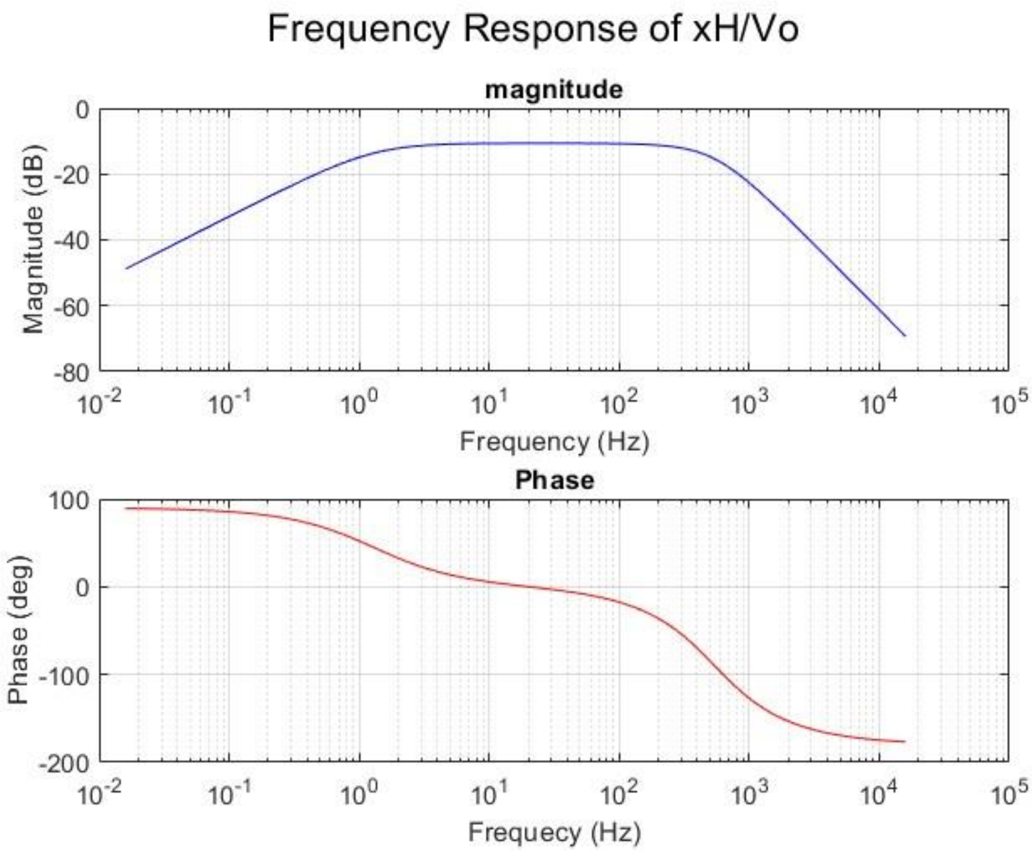
```
G =

                    7.959e-05 s
  ----------------------------------------------------
  2.341e-11 s^3 + 1.373e-07 s^2 + 0.0002716 s + 0.002205
```

(14)

Frequency Response

Finally, a bode plot and phase diagram can be found through this transfer function. The bode plot shows that between 0.02 to 1 Hertz is not an ideal frequency range because it is not level. Between 1 to 200 Hertz, the system settles. Finally, after 200 Hertz, the magnitude starts to drop off, indicating a not ideal frequency range. Also, because it is almost like a 1st order system, there is no resonance peak which shows that the system is safe for any frequency that is applied to it.

Figure 25. Bode plot of massage gun system with magnitude and phase.



Recommendations for Redesign

In conclusion to all this physical modeling, the main metric that can be changed to have a significant impact on the system is increasing the length of the crank. Many of the other variables that define this system do not have as much impact on it, such as the coefficient of friction and mass which go hand in hand if I were to change the material.

PROTOTYPING

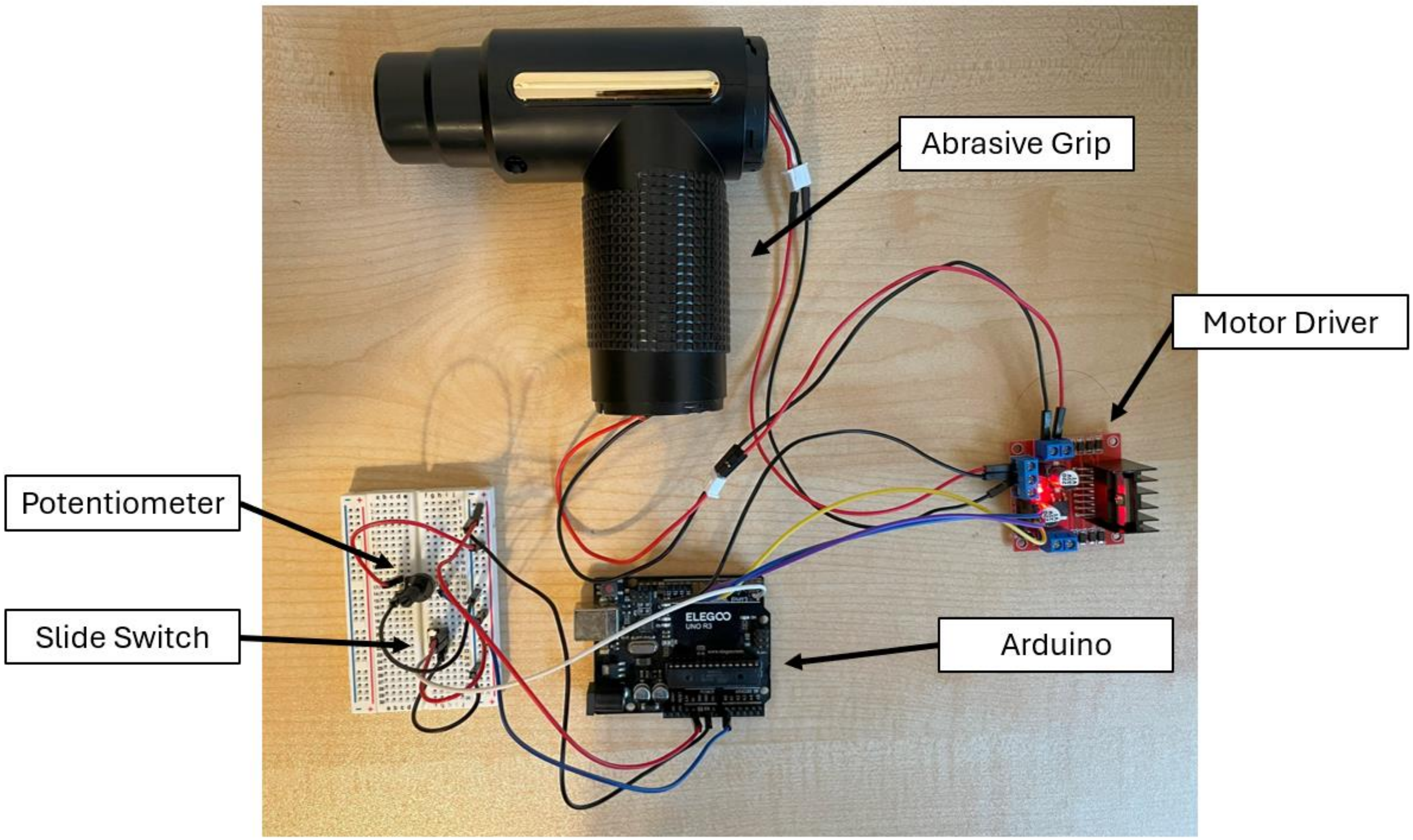
Prototyping is one of the final stages in the redesign process. At this point, the concept should be polished enough to bring it into the physical world. For the massage gun, I implemented most of the features from the final concept with some exceptions due to time and availability. The following sections explain in detail the low-resolution prototype and updated bill of materials.

Low-Resolution Prototype

Below is Figure 26 which shows the low-resolution prototype assembly for the redesigned massage gun. In this image, you can see there are five new components added to the massage gun. To emulate a "dial" I decided to use a potentiometer. This analog component adjusts the input voltage which in turn adjusts the motor speed via the Arduino microcontroller. Also on the breadboard is a slide switch. This takes the place of the single button by locking its on and off positions. I chose these two components because they fit nicely on a breadboard and demonstrate the functionality of the updated system without the need for aesthetics. Next to the Arduino microcontroller is the L298N motor driver. This board can connect with microcontrollers, a desired trait for prototyping. By writing a script and uploading that to the Arduino, I was able to adjust the speed with the potentiometer and actuate the electrical energy with the switch, two of the main functions of the final concept. To power the system, I reused the same LiPo battery that came with the massage gun and linked everything together with 20-gauge jumper wires. The last component in this prototype is the abrasive grip which is rubber tape that allows for a more secure grasp on the handle of the massage gun.

One of the features that does not appear on this prototype are the number stickers that display the speed in relation to the angular position of the potentiometer. Convenient ecommerce sites like Amazon did not have the size I imaged for the feature and more specialized sites had relatively long shipping times, so I decided to bypass this feature. In a high-resolution prototype, all the features from the final concept would be applied to the device and aesthetic features such as integrating a smaller microcontroller inside the housing and placing the new user interface (dial, slide switch, and stickers) where the existing interface lays.

Figure 26. Image of the low-resolution prototype assembly.



Updated Bill of Materials

Below is Table 10 which shows the components added to the bill of materials. Again, the pack of small stickers was not applied to the low-resolution prototype, but I intended to purchase them.

Table 10. Additional components to bill of materials.

Additional	21	1	Abrasive Tape	Recyclable HDPE Plastic	Black	
	22	1	Potentiometer	Metal	Grey	
	23	1	Pack of small stickers	Plastic	White	
	24	1	On/off switch	Plastic	Black	
	25	1	Arduino Uno	FR-4 Polyimide	Black	Microcontroller
	26	1	L298N	FR-4 Polyimide	Red	Motor Driver

FAILURE MODES AND EFFECTS ANALYSIS (FMEA)

In Table 11 below, I conducted FME analysis on my massage gun product. The main failure mode that emerged from this analysis was the open circuit for the DC motor that actuates the slider crank. The RPN for this mode was 270. The severity of this mode was 9 because if the motor circuit becomes open then there would immediately be a loss of electrical connection and the device would cease to work. The occurrence is 5 because this could occur occasionally because the user could drop the massage gun which would break the wire solder from the DC motor pins. The detection of this is 6 because this failure mode would not be that obvious without opening the massage gun. To access the motor, the bottom cap needs to be removed which can easily break due to the plastic clips that are used as fasteners. I recommend ensuring diligent and optimal soldering for the wires to the motor pins and possibly adding damping material on the inside of the housing to reduce the damage from an impact.

The next top failure mode is again with the motor and is ingress. If a liquid such as water enters the housing, then this could result in insulation degradation and/or corrosion. The RPN for this mode is 192. The severity is an 8 because this could result in a long-term issue that would require part replacements rather than a convenient DIY fix. The occurrence of this is a 4 because this could occur if a customer is not careful when handling the device around water and water sources are abundant. The detection is a 6 because it is not obvious if the liquid seeped into the housing without the user's knowledge. It would be somewhat hidden in the housing. A recommendation for this failure mode is to have better sealing in the housing.

Table 11. Design Failure Mode and Effect Analysis

☒ System ☐ Subsystem ☐ Component

Page: 1 of 1

Item: Massage Gun

Product/Model: M891 MINI

Core Team: Phillip Gavino

Part # & Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Cause(s)/ Mechanism(s) of Failure	Occurrence (O)	Current Design Controls/Tests	Detection (D)	Recommended Action(s)	RPN
DC Motor (12): Input rotational velocity and torque to slider crank for linear translation	Open circuit	Loss of electrical connection	9	Wire breaking off from solder due to force impulse (hitting, dropping), using massage gun at high intensity	5	Visual inspection, multimeter measurements	6	More secure soldering, damping material lining inside of housing	270
		Overheating				Thermistor, Infrared camera analysis			
	Ingress	Insulation degradation	8	Exposure to moisture, improper sealing	5	Visual inspection, physical inspection, megohmmeter	6	Better sealing in housing	240
		Corrosion				Multimeter, vibration analysis, dielectric testing			
	Stall	No actuation	8	Pressing too hard when massaging	6	Visual inspection	2	Instructions to not press down as hard as possible	96
		Overheating				Thermistor, Infrared camera analysis			

Crank Set Screw (17): Fixes crank to motor	Loose fitting	Rattling	8	Threads in crank are stripped	3	Auditory inspection, haptic inspection	7	Use a heated insert instead of directly tapping plastic crank	168
		Binding from slider crank translating at an angle				Manual movement test			
Slider (13): - the link that is translating linearly - a port for attachments	Vibrations	Loosen fasteners over time	5	Used massage gun at high intensity for a long period of time	3	Manual tightening, frequency analysis	5	Use lock tight	75
	Starved for Lubrication	Inefficient actuation	5	Dries up via light/thermal sources	5	Visual inspection	5	Apply generous amount of lubricant so it will last throughout device lifetime, keep out of light/thermal sources	125
		Increase friction and wear				Auditory inspection, infrared camera			
Bearing Outer Housing (14): - Holds the Bearing Inner Housing - Fastens to Main Body	Misalignment	Inefficient actuation	7	Threads not tapped/molded straight	2	Visual inspection	5	Ensure proper tapping/molding with quality control	70
		Increase friction and wear				Visual inspection, temperature monitoring			
	Binding	Motor stalls	9	Threads not tapped/molded straight	3	Load testing	5	Ensure proper tapping/molding with quality control	135
		Overheating				Thermistor, Infrared camera			
Main Body (1): - Secures components - Protects components	Cracking	Liquids or debris could go into housing	6	Dropping or hitting device	7	Hardness testing, impact testing	3	Material with moderate impact protection	126
	Fracture	Components could fall out and get damaged	8	Dropping or hitting device	7	Hardness testing, impact testing	3	Material with moderate impact protection	168

CONCLUSION & FUTURE WORK

The goal of this project was to reverse engineer a massage gun device to improve it in some way. An overarching design methodology flow was utilized to achieve this objective. The first step was to establish the mission statement and ask myself technical questions to better understand the scope of the project and what needed to be focused on. Next, by doing thorough customer needs analysis through interviewing potential users, a detailed weighted list of these needs became the basis of what needed to be improved. Functional modeling was the next step in the process. There were two different versions of the modeling, the first being a predicted model before dissecting the device and the second being after dissecting it. This modeling was very useful for understanding the system broken down to its functions rather than features. Following this, qualitative function deployment using a house of quality was used to connect customer needs with performance metrics. These metrics were used in the adaptive and parametric redesigns. For the adaptive redesign, concept generation techniques allowed for the emergence of creative solutions to enhance the “adjust speed” function. A final concept was the result of this concept generation and selection by using the Pugh chart approach to systematically evaluate the validity of concepts. For the parametric redesign, a mathematical model was created via bond graphs to optimize one of the performance metrics. I discovered that the crank of the crank-slider was exactly half of the stroke length, a very valuable insight from this process. After the two different redesign methods, a low-resolution prototype was created which embodied some of the features from the final concept.

The next step for this project would be to create a high-resolution prototype. This design would incorporate all the final concept features in a more aesthetic way than what it is currently. 3D printing technology would be used to create custom housings for the user interface features and the ergonomic improvements would have a more professional look to them.

CRITIQUE OF METHODOLOGY

The overall design methodology process felt effective through its systematic and organized approach to product design. Something I would change about the process though was the concept generation portion of the project. I really enjoyed learning about design by analogy from Dr. Wood’s guest lecture and would have liked this to be a required choice to the C-Sketch method rather than an additional optional one.

The amount of work for this project seemed reasonable with assignments spread out through the semester but combining them into a final report was arduous. I believe having class activities as participation grades and the assignments as actual grades would be a nice change.

Overall, this project pushed me to have a better understanding of the design process and gave me the confidence to apply the engineering methods I have learned throughout my academic career.

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APPENDIX A: MORPHOLOGICAL MATRIX

Figure A.1. Solution 1 morph matrix.

Category	Subfunction	Current Solution	Other Solutions		
Motion	Convert EE to Mech E Rot	PMDC Motor	Brushless DC Motor	Stepper	Servo
	Convert Mech E Rot to Trans	Slider Crank	Linear Actuator	Rack and Pinion	
Ergonomics	Import Hand	Cylindrical	Pistol Grip	Deformable Grip	Abrasive Grip
	Position	Hand	Hooked Extension	Stick	
	Stabilize	ABS	Carbon Fiber	PLA	PETG
Speed Control	Adjust Speed	Button	Multiple Buttons Dial	Slider	Touchscreen
	Display Speed	LED Lights	LED Screen Stickers	Touchscreen	Engraved
Power Supply	Import EE	USB C	Directly from Outlet Cord	Hand Crank Generator Port	Solar Panel Port
	Store EE	LiPo Battery	Alkaline Battery		
Controls	Actuate EE	Button	Switch		
	Sense Force	Current Feedback	FSR	Mini Scale	

Figure A.2. Solution 2 morph matrix.

Category	Subfunction	Current Solution	Other Solutions		
Motion	Convert EE to Mech E Rot	PMDC Motor	Brushless DC Motor	Stepper	Servo
	Convert Mech E Rot to Trans	Slider Crank	Linear Actuator	Rack and Pinion	
Ergonomics	Import Hand	Cylindrical	Pistol Grip	Deformable Grip	Abrasive Grip
	Position	Hand	Hooked Extension	Stick	
	Stabilize	ABS	Carbon Fiber	PLA	PETG
Speed Control	Adjust Speed	Button	Multiple Buttons Dial	Slider	Touchscreen
	Display Speed	LED Lights	LED Screen Stickers	Touchscreen	Engraved
Power Supply	Import EE	USB C	Directly from Outlet Cord	Hand Crank Generator Port	Solar Panel Port
	Store EE	LiPo Battery	Alkaline Battery		
Controls	Actuate EE	Button	Switch		
	Sense Force	Current Feedback	FSR	Mini Scale	

Figure A.3. Solution 3 morph matrix.

Category	Subfunction	Current Solution	Other Solutions		
Motion	Convert EE to Mech E Rot	PMDC Motor	Brushless DC Motor	Stepper	Servo
	Convert Mech E Rot to Trans	Slider Crank	Linear Actuator	Rack and Pinion	
Ergonomics	Import Hand	Cylindrical	Pistol Grip	Deformable Grip	Abrasive Grip
	Position	Hand	Hooked Extension	Stick	
	Stabilize	ABS	Carbon Fiber	PLA	PETG
Speed Control	Adjust Speed	Button	Multiple Buttons Dial	Slider	Touchscreen
	Display Speed	LED Lights	LED Screen Stickers	Touchscreen	Engraved
Power Supply	Import EE	USB C	Directly from Outlet Cord	Hand Crank Generator Port	Solar Panel Port
	Store EE	LiPo Battery	Alkaline Battery		
Controls	Actuate EE	Button	Switch		
	Sense Force	Current Feedback	FSR	Mini Scale	

Figure A.4. Solution 4 morph matrix.

Category	Subfunction	Current Solution	Other Solutions		
Motion	Convert EE to Mech E Rot	PMDC Motor	Brushless DC Motor	Stepper	Servo
	Convert Mech E Rot to Trans	Slider Crank	Linear Actuator	Rack and Pinion	
Ergonomics	Import Hand	Cylindrical	Pistol Grip	Deformable Grip	Abrasive Grip
	Position	Hand	Hooked Extension	Stick	
	Stabilize	ABS	Carbon Fiber	PLA	PETG
Speed Control	Adjust Speed	Button	Multiple Buttons Dial	Slider	Touchscreen
	Display Speed	LED Lights	LED Screen Stickers	Touchscreen	Engraved
Power Supply	Import EE	USB C	Directly from Outlet Cord	Hand Crank Generator Port	Solar Panel Port
	Store EE	LiPo Battery	Alkaline Battery		
Controls	Actuate EE	Button	Switch		
	Sense Force	Current Feedback	FSR	Mini Scale	

APPENDIX B: BACK OF ENVELOPE CALCULATIONS