DESIGN OF A MOTORIZED PROSTHETIC FOR DRIVING AN AUTOMATIC VEHICLE IN ONTARIO

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EXECUTIVE SUMMARY

Hand amputees that wish to drive a vehicle use a combination of driving aids, often requiring modification of their vehicles [1]. A team of 2 University of Waterloo students designed and developed a prototype motorized prosthetic with the goal of removing the need for hand amputees to modify their vehicle in order to drive. The prosthetic, consisting of a clamp mechanism, can be opened with a servo motor triggered by an EMG signal from the user. Validation was performed to determine the prototype's viability; based on calculations, the force output must be increased to rotate a steering wheel during a turn, but the prototype is capable of gripping a wheel and assisting rotation.

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I. INTRODUCTION

Hand amputees may wish to drive an automatic vehicle. Products on the market exist to allow users with one hand to drive safely. These include "knob grips" for assisted steering, as well as other modifications to the car to allow for gear shifting, use of the lights, use of automatic-window controls, and use of the turn signal [1, 2]. These modifications improve safety but are difficult to transfer between vehicles. Modifications often require that the user's hand is always on the wheel (or on a knob grip), reducing the user's ability to do tasks like using the radio. Mechanical prosthetics may be used in combination with vehicle modifications to reduce this issue. The prosthetic holds a steering aid attached to the wheel, allowing for two-handed driving; however, additional modifications are still required for use of the headlights, turn signal, and automatic-window controls [1, 3]. This results in a more complex solution, with many aids and car modifications.

To alleviate these problems, a motorized prosthetic was designed to allow left-hand amputees in Ontario to drive a car without any modifications. The prosthetic was intended to be able to grip and release the wheel via EMG signal. The user, then, would be able to utilize their turn signals, horn, centre console controls, headlight controls, and steering-wheel-buttons while driving.

II. DESIGN PROCESS

The prototype was designed via a combination of linear/waterfall and agile/iterative design process models. Fig. A.1 shows a prescriptive design model from [4]. Deviations were made to the model and are described in the following subsections.

A. Problem Definition

A problem statement and a project objective were created (see Section I). Project requirements were established based on these and are tabulated below.

TABLE 1. PROJECT REQUIREMENTS

ID.	**Description.**	**Test Protocol.**
Functional Requirements.		
R1.	Shall be able to open/extend and close/flex "fingers" in order to grip/release a steering wheel.	N/A

R1.1.	Shall exert enough force to rotate a steering wheel during a turn.	Measure force exerted by motorized “fingers.”
R1.2.	Shall utilize a motor for finger extension (such that flexion is the resting state of the mechanism), triggered by an EMG signal sent to an Arduino Uno.	Observe and document qualitatively the prototype’s ability to complete an open-close cycle.
R2.	Shall be able to utilize turn signals.	N/A.
R3.	Shall be able to utilize car horn.	N/A.
R4.	Should be able to utilize headlight controls.	N/A.
R5.	Shall have a Factor of Safety (FoS) of at least 1.5 on all physical components of the end effector as well as the servo.	Run an FEA on the physical components that should undergo stresses and compare outputs to known yield stress values from literature. Calculate the maximum torque required of the servo by the design.
User Requirements.		
R6.	Shall be comfortable to exert force on the steering wheel for an extended period of time.	Test user(s) shall rate comfort of moving the motorized component of the prosthetic on a Likert scale (1-5).
R7.	Shall be comfortable to open "hand" / extend "fingers."	
R7.1.	Should have “closed hand” as the resting state.	N/A.

While design constraints were not formally documented, it should be noted that the prosthetic had to be designed within 3 months, could be actuated/powered by at most 1 servo and 8 1.5V batteries, and was limited to 3D printed and basic hardware (nuts, bolts, threaded rods, springs). The servo and battery constraints were to reduce the size and weight of the prosthetic.

B. Conceptual Design

Functional requirements were adapted into principal functions, F1 and F2. Three possible implementations/means of F2 were ideated and are tabulated below. F1’s implementation was designed iteratively during the preliminary design phase and is discussed in Section IV-A.

TABLE 2. MORPHOLOGICAL CHART

Functions.	**Means.**		
	1	**2**	**3**
F1. Detect an EMG signal and convert it into a “stop/go.”	N/A.	N/A.	N/A.
F2. Open/extend and close/flex a mechanical replacement for fingers.	Singular “finger” mechanism that wraps around the steering wheel as wires pull the tip of the “finger” down to the “palm.”	Clamp mechanism where two flat surfaces are pulled apart by a servo, with tensile springs resisting the motion. When the servo is inactive, the force of the springs bring the surfaces back together.	Same clamp mechanism seen in (2) with elastics used as the return mechanism.

A design concept was ideated based on the selected means (with respect to F2). Design sketches were generated and used as a basis for the end effector during the following design stages. Calculations were performed to determine force outputs, critical values for testing, and key part dimensions.

C. *Preliminary and Detailed Design*

The following two stages of the design process were performed iteratively for each sub-system. Mechanical components were designed using the workflow in Figure A.2.

Circuitry was designed according to the following steps:

1. determine input properties from literature (e.g., bounds on frequency of EMG signal),
2. determine output requirements (e.g., high resolution signal vs binary),
3. record common circuitry practices from literature; and,
4. select components based on common engineering practice and output requirements.

Code was designed around the output of the completed circuitry, iteratively determining the steps/algorithms required to convert the signal to binary instructions for the servo. Literature was consulted for recommended steps.

System-level performance was tested/validated according to the test cases for R1 as described in Table 1. Each sub-system’s performance was validated according to its respective validation process as described in Table 3.

TABLE 3. SUB-SYSTEM VALIDATION PROCESS

Sub-system.		**High-level validation process description.**
Motor.		See validation plan for R5 in Table 1.
End effector.		See validation plan for R5 in Table 1.
EMG circuitry.	Filters.	Record the experimental change in gain at varying frequencies; compare recorded values to theoretical values.
	Amplifiers.	Record the experimental change in gain of the signal based on an assumed input value from literature.
	Additional components.	Qualitatively validate the effect the components have on the signal as read by the microcontroller (i.e., perform a manual end-to-end test, comparing the output of the circuit with the component relative to the output without the component).
Microcontroller and code.		Qualitatively validate the change each signal processing mathematical operation has on the signal as read by the microcontroller (i.e., perform a manual end-to-end test, comparing the output to the servo with the operation relative to the output without the component).
Housing, attachments, battery pack.		N/A.

Sub-systems were developed sequentially in the following order: motor selection, end effector, EMG circuitry, microcontroller and code, and housing. See Section IV.

III. PROTOTYPE AND SYSTEM-LEVEL PERFORMANCE

An image of the fully assembled prototype can be seen in Fig. 1.

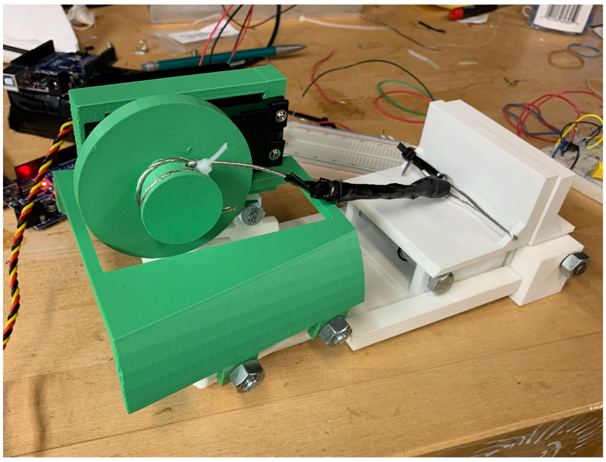

Fig. 1. Completed prototype.

The completed prototype utilizes a clamp mechanism pulled to the “closed” position by springs. A spool of radius 12.73mm (as calculated in Appendix B) rotates 180 degrees with an HS-805BB servo motor to open the clamp mechanism by pulling a wire (a picture-frame hanging wire rated for 30lbs) such that its available horizontal-length decreases by 40mm.

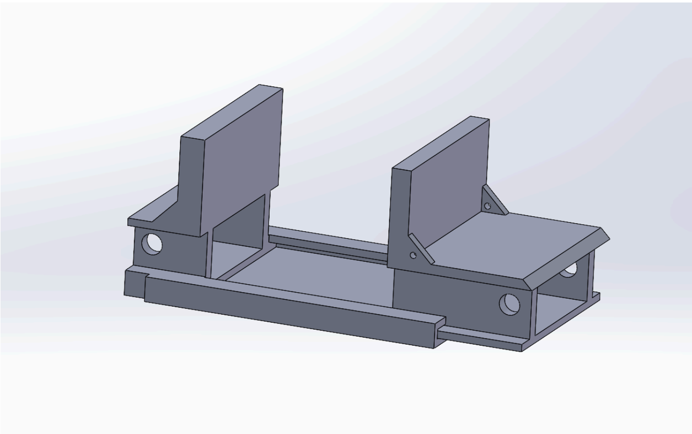

Fig. 2. Assembly view of completed clamp mechanism.

Housing and an arm attachment (gauntlet) were designed. The arm attachment connects to the forearm via velcro straps which thread through holes in the gauntlet. The gauntlet is composed of two components connected by ¼” bolts. The first attaches to the clamp mechanism via a threaded rod and sits on the forearm extensors; the second houses the servo and sits against the forearm flexors. Housing was designed to fit on the bicep (also secured with velcro), sized and toleranced to hold two battery packs (each holding four 1.5V batteries), one breadboard, and one Arduino Uno.

Circuitry and code were designed; a schematic of the circuitry can be seen in Fig. D.1; the full code can be seen in Appendix E. An outline of the signal processing workflow can be seen in Fig. 3.

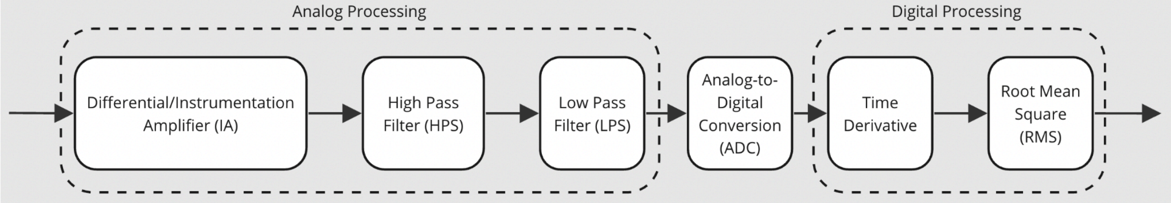

Fig. 3. Signal processing workflow.

The validation criteria for system-level performance described in Section II was used and tabulated below. Validation was graded on a 3-level scale: FAIL, PASS WITH CONCESSIONS, PASS. See Appendix B for information on the critical values.

TABLE 4. SYSTEM-LEVEL VALIDATION

Measured Parameter.	**Critical Value.**	**Validation Protocol.**	**Results.**
Observation of the prototype's ability to complete an open-close cycle, triggered by an EMG signal.	N/A.	See validation plan for R1.2 in Table 1.	*PASS WITH CONCESSIONS.*
Force exerted by clamp when opened to minimum grip-diameter.	50N.	See validation plan for R1.1 in Table 1.	*PASS WITH CONCESSIONS.* .

The prototype was capable of responding to an EMG signal and completing an open-close cycle; however, occasional misfires of the servo were observed, caused by noise values with large enough magnitudes to be mistaken for signal.

Simulations showed that the sliding component would be capable of withstanding the stresses caused by the springs and servo. Calculations determined that the force of the springs would not exceed the servo's stall torque and would meet the required FoS of 1.5. However, the gauntlet component was not simulated; during testing it was observed that the base of the gauntlet would bend when the clamp was in the open position. The large bending moment was likely due to the gauntlet base's low moment of inertia. The spool was also not fixed to the servo, and could be pulled off by the servo after ~3 (open-close) cycles. The force exerted by the clamp was reduced to prevent these oversights from affecting the prototype's ability to open and close.

Overall, the prototype meets the key requirement of being able to open-close in response to an EMG signal such that it can grab a steering wheel. Changes need to be made to the gauntlet component to prevent bending; specifically, the moment of inertia must be increased (i.e., the base of the prosthetic must be thicker). The spool must also be fixed to the servo.

IV. PROTOTYPE SUB-SYSTEMS

A. Motor

1. Initial Motor Selection

It is worth noting that the basic design of the end effector (seen in Fig. 4) was designed before motor selection occurred. The initial motor selection was performed using a calculated maximum torque value of $54.75\ \text{N} \cdot \text{cm}$. This value was determined by resolving a relationship between the torque output required of the servo and the grip force necessary to generate a 30N friction force to rotate the wheel. Given its high maximum torque (202.12 $\text{N} \cdot \text{cm}$) and speed (188 ms), the HS-805BB was selected [9]. While speed was not a formal requirement it was a consideration as driving is a dynamic task.

It is worth noting that these calculations were later redone after compression springs were selected and measured. See Appendix B for complete calculations and Section IV-A-2 for information on the redone calculations.

2. Subsequent Motor Calculations

In the design, the servo is attached to a spool, which houses a string threaded through the sliding block. When the servo rotates back, it pulls the sliding block back the distance that the spool attachment rotated. This is equal to the spool radius, multiplied by the angle of rotation in radians. The torque required of the servo linearly increases as the radius of the spool (distance from the center of the servo) increases. When the clamp is open 22mm, a 50N grip force is required; it can be noted that this differs from the initial calculations, yielding a maximum torque of $116\ \text{N} \cdot \text{cm}$ (see Appendix B).

Since the servo has to withstand large forces, the radius of the spool should be minimized, meaning that the servo will rotate 180 degrees to fully open the mechanism. This yielded a spool radius of 1.273cm.

It turns out that only the HS-805BB motor exceeds the required factor of safety of 1.5, meaning that it is the only suitable choice for the prosthesis.

B. End Effector

It was decided that the most suitable end effector for the task of driving would be a clamp mechanism made up of a stationary guide rail, and a sliding block. It is compact, simple, and offers a large area to grip the steering wheel. An initial conceptual design of this end effector can be seen in Fig. 4.

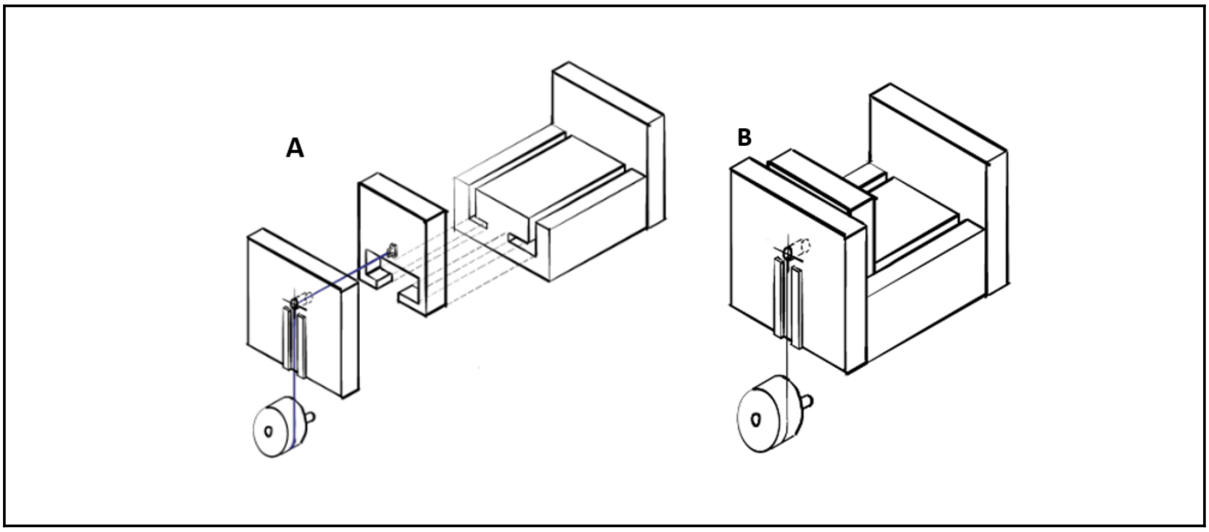

Fig. 4. Design sketches of the clamp mechanism; exploded view (A); assembly view (B).

This mechanism can only be powered by a few batteries. Since the motor draws large amounts of current, the time the part spends moving must be minimized. As well, the device is controlled by the user actively flexing their forearm muscle. This would be rather uncomfortable to do for extended periods of time, therefore, the user should only have to flex their muscle in short bursts.

In order to satisfy these requirements, the clamp needs to be in its most frequent position when the user is not flexing their forearm: closed. If the clamp is closed for the majority of the drive, the current-drawing motor should not be applying the force to keep it closed. The sliding block already has to change its distance from the guide rail to grip and release the steering wheel. This made springs the ideal mechanism to hold the prosthesis closed. Fig. 5 below shows an initial design of the sliding block and guide rail mechanism. Due to limited availability of hardware, and a need to output a large force (see Appendix B), four springs were incorporated into the design. They were to be super glued in the holes seen in the design.

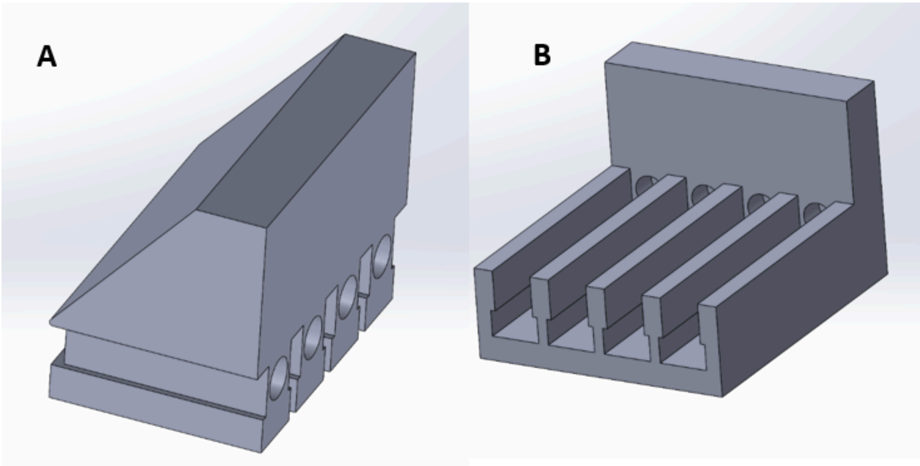

Fig. 5. CAD Models of the Sliding Block (A), and Guide rail mechanism (B).

Since the average thickness of a wheel is typically between 2.22cm to 3.44cm, the distance between the walls of the sliding block and guide rail were decided to be 4cm at full open [5].

Before printing the models seen in Fig. 5, using known relationships identified in Appendix B, the maximum force exerted by each spring, as well as the maximum torque exerted on the servo were resolved. Results are tabulated in Table B.1. FEA analysis was also conducted on the sliding block to ensure the design could withstand the stress of the springs and the servo, which can be seen in Fig C.1. It should be noted that since the springs being used are known, these are now experimental values, rather than the desired theoretical values considered for motor selection. After calculating these values, it was deemed that this design was within a factor of safety of 1.5 (taking the yield stress of PLA to be ~40MPa based on [6].

Once the design was materialized, it was noted that the part was very large and used unnecessary amounts of material. Furthermore, the planned super glue mechanism of holding the springs was not strong or reliable enough; they needed to be mechanically attached.

Information from FEA analysis was used to identify and remove excess material (i.e., material that did not undergo much stress was removed). The design was changed such that the sliding block and guide rail contained holes for bolts where springs would mechanically attach. This provides a more reliable mechanism to close the clamp. Fig. 3 Below shows the new (and final) end effector CAD model. As with the previous design, FEA analysis showed that the design (though experiencing more stress) was well within the required factor of safety of 1.5.

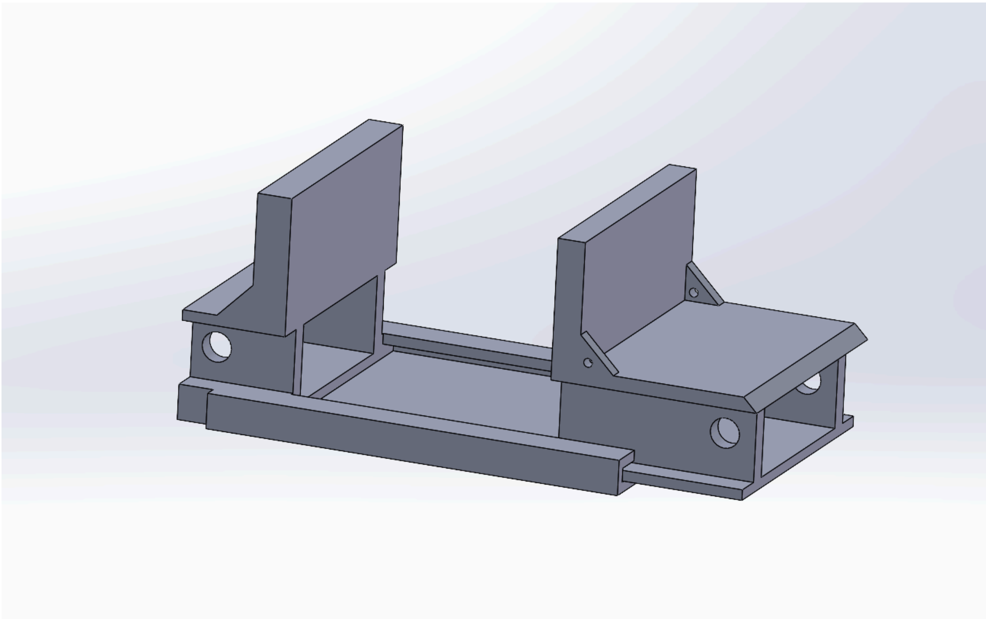

Fig. 6. Final CAD models of the sliding block and guide rail mechanism.

This final design used far less material than the original, moved easier along the guide rail, and was more mechanically sound. Upon physical testing, it was determined that the design could easily withhold the full force of all four springs. This means that the design is rated for up to 85N of force (for a 4cm thick wheel). Using the k constant derived in Appendix B, and noting that a normal force of 50N is required on the wheel, this prosthesis is able to support steering wheels with a thickness greater than or equal to 2.36cm. It should be noted that since the design is only able to stretch 4cm, it is not recommended for wheels close in thickness to this value.

When incorporated with the final design, the servo motor will attach to a string which will thread through holes in the back of the sliding block seen in Fig. 6. As the user flexes their forearm muscle, the change in signal strength will be picked up by the microcontroller, which will cause the servo motor to rotate back. This will pull the string connected to the sliding block, and cause it to travel back, thereby opening the clamp. As soon as the user stops flexing their forearm, the servo will travel back to its original position, allowing the springs to exert force, bringing the sliding block back to the guide rail until it closes on the steering wheel and remains in this position until it receives a signal that instructs it to open.

C. EMG Circuitry

A high-level overview of the EMG circuitry can be seen in Fig. 3. The bandwidth of the EMG signal was taken to be between 0.1Hz and 450Hz, validated by the cutoffs chosen in a similar circuit described in [7]. It was decided that a high-pass filter with a cut-off of 80Hz would be used to reduce the 60Hz noise without significantly affecting the signal (in consideration of the main frequencies appearing to exist around ~100Hz) [7]. A low-pass filter with a cut-off of 461Hz was used to remove high frequency noise. A second order high-pass filter was considered but ultimately discarded due to unusual results during testing with a function generator. The first order high-pass filter used in the prototype was made active via a LM-358 operational amplifier, configured as a non-inverting amplifier via a 2000 ohm (Ω) (to ground) and a 1MΩ resistor (from the inverting terminal to the output terminal). This yielded a gain of ~500x, which when limited by the rail/supply voltage of the LM-358 results in the signal theoretically utilizing the entire rail voltage.

Three electrodes were placed on the test-user's arm (two on the anterior of the forearm, with the first placed approximately on the head of the largest superficial forearm flexor by observation and the second placed slightly above and lateral to the first; the third was on the elbow to ground the test-user). Electrodes would be repositioned experimentally to increase the resolution of the signal. An AD-623 Instrumentation Amplifier (IA) outputs the difference between the two electrodes on the anterior forearm, theoretically removing noise resulting from the electrodes. A gain setting resistor of 1000Ω was used with the IA for a theoretical gain of 100x Assuming a raw signal voltage of 0.1mV, experimental gain values were determined by probing the circuit after each amplifier; the IA gain was observed to be ~80x, and the AD-623 gain was observed to be ~50x. The difference in IA gain between the expected and real value may be due to: the assumed initial signal voltage, the tolerancing on the resistor (5%), or manufacturing and human error.

The required output (based on F1) was a "stop/go" signal, meaning the signal had to be converted to binary. Discussions were had whether rectification would be necessary due to signal lost from the 0V rail voltage of the amplifiers. Rectification was tested but ultimately unused due to its minimal effect on the final signal as read by the microcontroller. Both filters were validated per the validation plan in Table 3; bode plots were generated and can be seen in Appendix D. Amplifiers were validated per Table 3; theoretical and real gain values are described above. Rectification was ultimately unused due to validation per Table 3.

Simulations were run in Falstad [8] for each added/changed component of the circuit (with the exception of the IA, which was not simulated); a complete circuit schematic can be viewed in Fig. D.1, made using Falstad.

D. *Microcontroller and Code*

The output signal from the circuitry was viewed in the Arduino Serial Plotter to determine required algorithms that the code would need to perform. Note that the Serial Plotter was utilized in validating the unused rectifier. It was observed that oscillations in the signal would need to be “smoothed” to yield a “stop/go” signal; one suggested solution was to simply add a time delay when the motor is triggered (i.e., rotated 180 degrees due to a read voltage greater than some threshold to open the clamp). This is simpler computation than “smoothing” the signal, but reduces user control of the motor, as it means the clamp is open for a set amount of time regardless of the amount of time the user flexes their forearm. It was decided that taking the Root Mean Square (RMS) of the signal could “smooth” the signal, allowing the user full control of when the motor is triggered and for how long.

It was thought that a derivative may reduce calibration requirements, as the rate of motor neuron conduction can be assumed to be more similar between users than the magnitude of their muscle flexion. This was not proven experimentally, but the derivative algorithm was validated per Table 3.

The full code can be seen in Appendix E.

E. *Housing, Attachments, Battery Pack*

The final prosthesis contains one breadboard with the EMG circuitry, one Arduino microcontroller, and two battery packs, each containing 4AA batteries. It was planned that only one battery pack would power the whole design, through the Arduino. However, the HS-805BB servo used in the design at maximum torque output draws upwards of 3A [9]. This would draw current away from the amplifiers, altering the signal, and potentially drawing too much current for the Arduino. As such, it will need to be powered by a separate battery pack.

While the current drawn of the servo is large, and if run constantly, would rapidly drain the batteries, it is acceptable in the design due to the frequency that the servo experiences load. As mentioned previously, the clamp remains closed for the majority of a drive, meaning that for most of the time, power draw is minimal. When the clamp is open, it will only be for very brief periods of time to make adjustments on the steering wheel. Because of this, the average current draw coming from the servo will be low.

Fig. 7 below illustrates the design for the housing for all important circuitry.

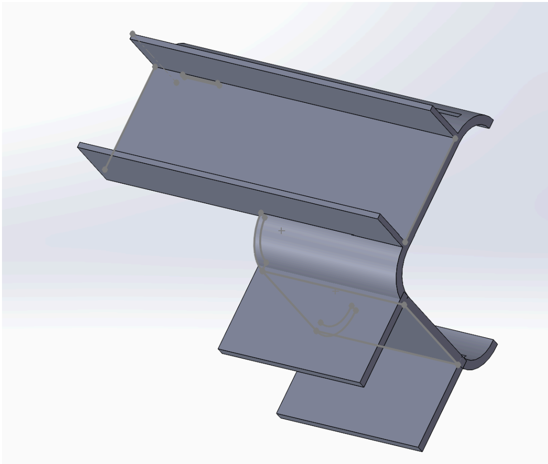

Fig. 7. Housing for circuitry.

The large top segment of the housing serves as a point where the breadboard containing all circuitry could be adhesively attached. The second, smaller segment serves as a point where the Arduino microcontroller, and battery packs are able to attach, vertically stacked on top of one another.

In addition to requiring housing for circuitry, the end effector needs a way of attaching to the user's forearm. In the prosthesis, a gauntlet-like device is used to attach and secure the clamp to the user's forearm. The gauntlet device consists of two pieces that mechanically fasten to each other using bolts. This can be seen below in Fig. 8.

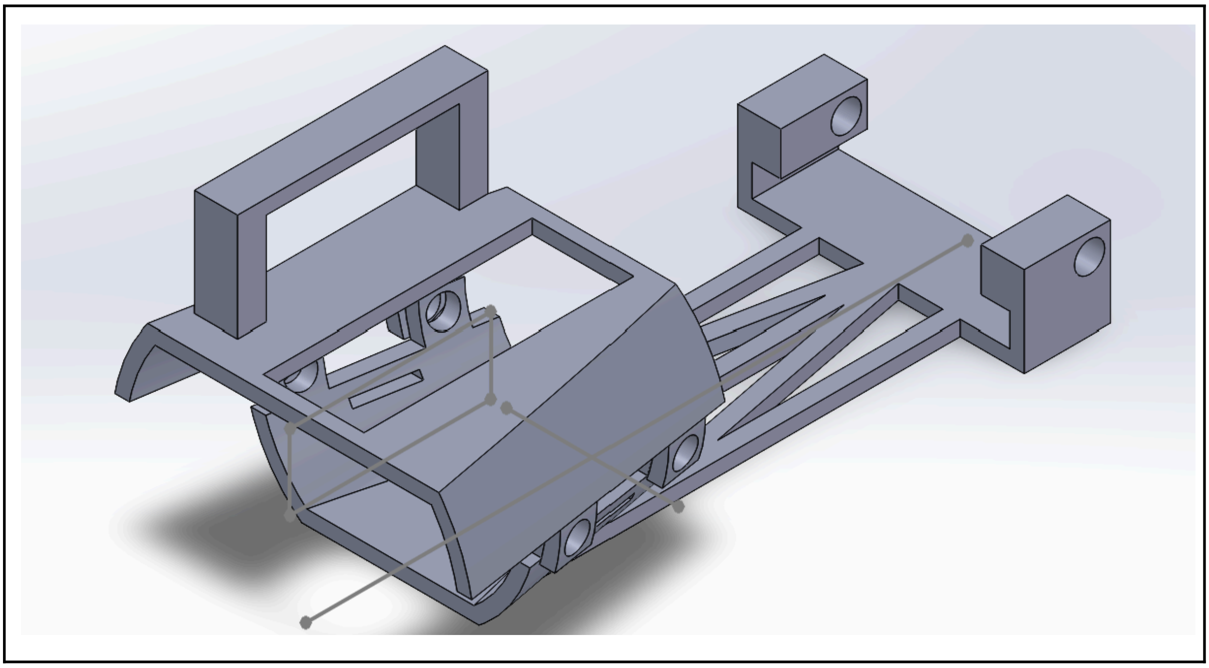

Fig. 8. Gauntlet piece pictured with Guide Rail.

The two back pieces seen in Fig. 8 have two holes on each side that allow for a small bolt to fasten through and attach the pieces together. At the front end of the gentlet piece, there is an extension where two more bolt holes are present. This allows the gauntlet to mechanically fasten to the guide rail with a threaded rod, creating a strong attachment point between the forearm attachment and the end effector. Fig. 9 illustrates the prosthetic with the end effector attached.

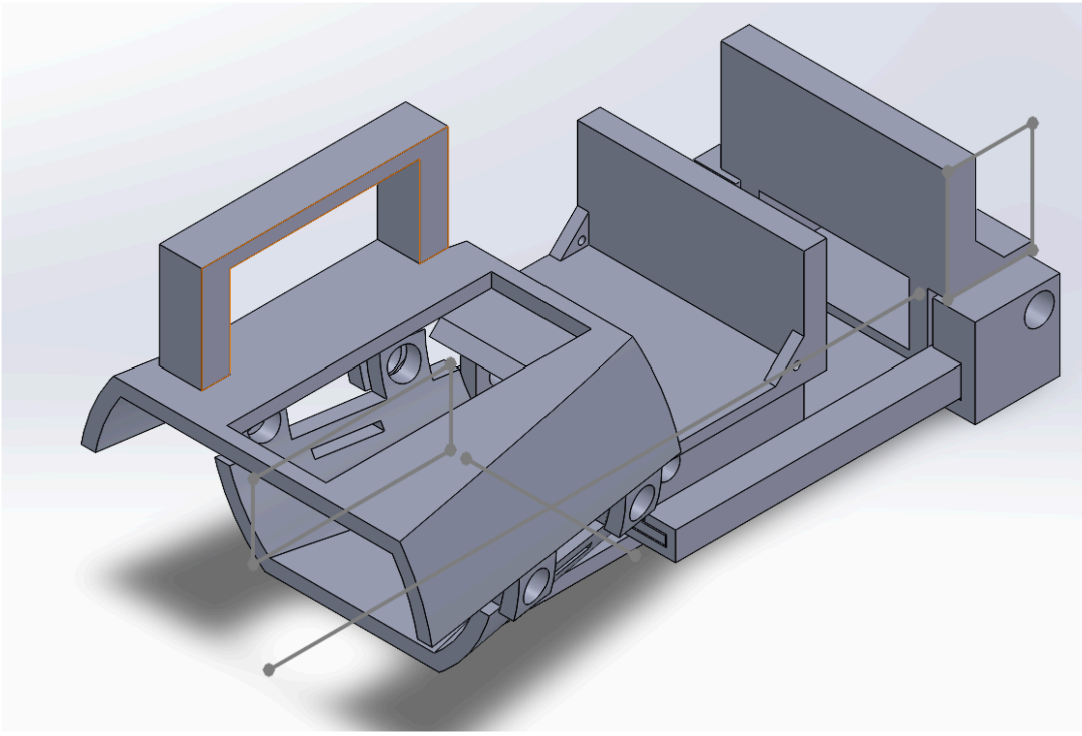

Fig. 9. Gauntlet piece attached to end effector.

In the final design, the gauntlet is mechanically fastened to the guide rail, which houses the sliding block. Since the sliding block needs to move, it cannot be bolted to the forearm attachment. It should be noted, however, that the user's forearm, as well as the gauntlet itself, prevents the sliding block from falling out of the design. This minimizes the safety risk that the sliding block may detach from the design.

V. CONCLUSION

The prosthesis designed was minimally able to alleviate the problems identified with one-handed driving. Though the driver cannot use the prototype to utilize their headlights, they can still steer the car, use the turn signal, and use their horn, though not to the same degree as initially planned. Poor final design priorities lead to a prototype that while low in material usage, provided little resistance to the forces and moments exhibited on the user. FEA analysis was only performed on the areas of maximum stress, and no simulation was used to understand the mechanics of the entire system. This led to a thin attachment that is unable to withstand the bending caused by the servo at the intended torque, forcing the design to lose 75% of its springs, and significantly lowering its force output. Though a minimally functional prototype was presented as initially desired, it has design flaws to correct before it becomes viable for real-world use.

The end effector mechanism works effectively, and in an isolated environment, is able to handle the full force expected of it. The gauntlet attachment; however, needs to be redesigned to become viable. The part is too thin, given that it will be subjected to a bending moment by the servo when the clamp is opened. In order to alleviate this, sufficient material needs to be added away from the neutral axis for the bending load. This means that the part needs to increase in thickness where the end effector and attachment articulate.

Furthermore, to make this prosthesis fully viable, simulation of the entire system needs to be performed. Additional weak points that have not been considered need to be identified and solutions need to be put in place that are supported by FEA analysis. As well, the prosthesis should incorporate some type of fine movement, perhaps through a second motor, to be able to utilize the high beams as initially planned. Once an improved solution is presented that delivers on all expected features, and is able to output the expected force with minimal deformation, user testing needs to take place. The design needs to be tested by users, and feedback should be incorporated into several iterations of redesign until a functional, and comfortable solution is formulated.

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Appendix A: Additional Figures

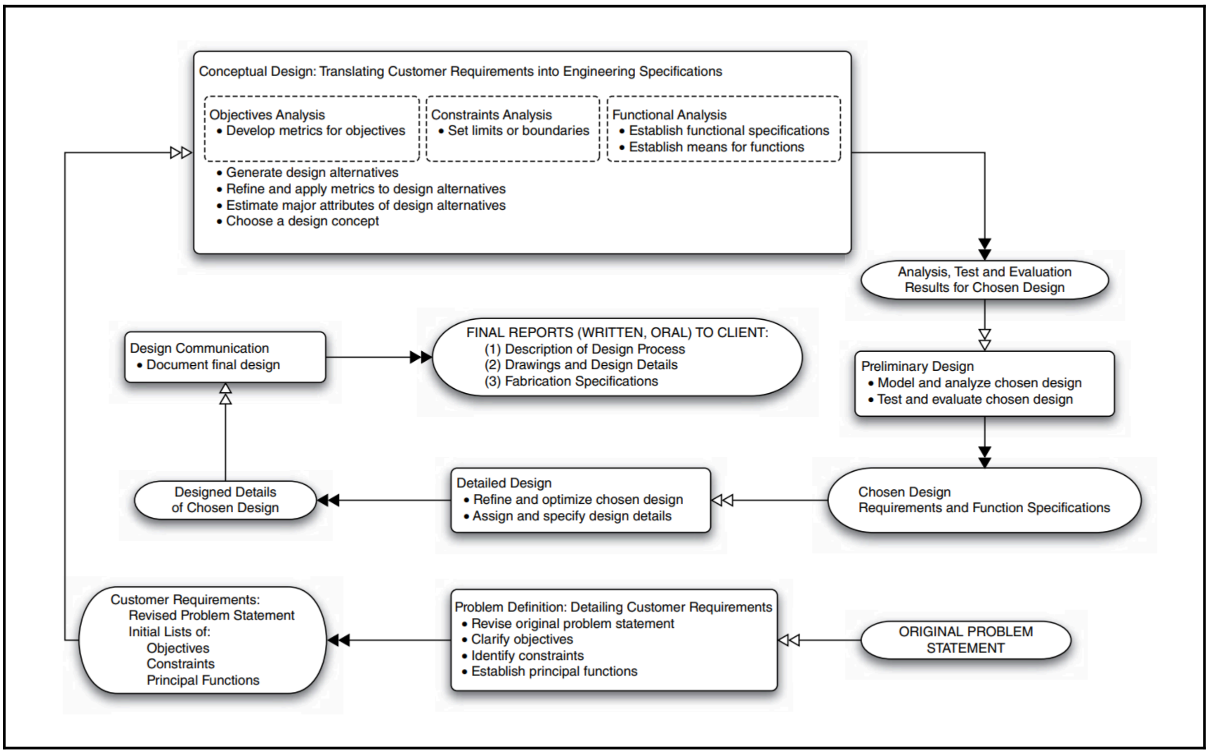

Fig. A.1. Five-stage prescriptive model of the design process.
Rectangles represent stages, ovals represent ovals.
Source: [4]

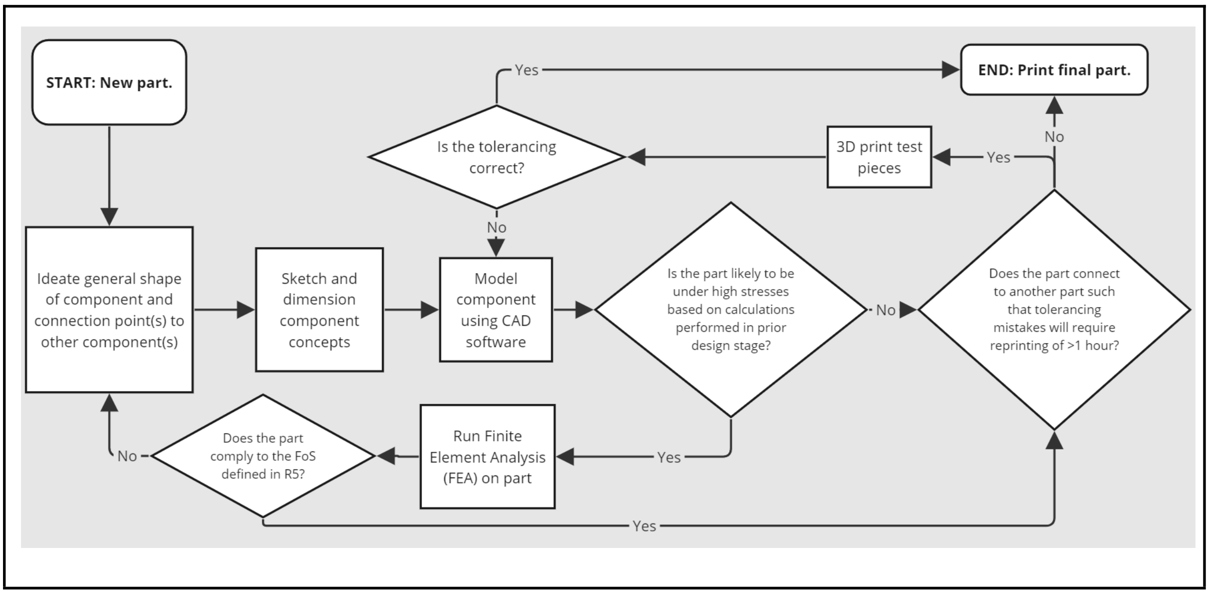

Fig. A.2. Design process for mechanical components.
Diamond-shaped boxes represent decisions, square-shaped boxes represent steps; "test pieces" refer to 3D printed mechanical components of which only a section was printed to ensure correct tolerancing at a connection point with another mechanical component.

Appendix B: Significant Calculations for Mechanism Design

Steering wheels range from 22mm to 34mm [5]. The spring mechanism of the clamp means torque requirements of the servo increase as the clamp opens. The clamp must open more than 34mm; 40mm was chosen for tolerancing. The servo must be capable of providing a torque (T) such that the spring can be stretched 40mm in order to open the clamp mechanism.

$$T = 40 \cdot k \cdot N \cdot r \quad \text{Eq. (B.1)}$$

Where N represents the number of springs in the mechanism, k represents the spring constant in N/mm, and r represents the distance between the center of the servo and the string it is pulling.

The clamp must exert enough force to create a frictional force (between the clamp and steering wheel) greater than 30N [10]. The coefficient of static friction was taken to be 0.6 based on [11].

$$F_N = \frac{30}{0.6} = 50 \qquad \text{Eq. (B.2)}$$

The springs need to exert a force exceeding 50N when stretched 22mm, the low-end of the average width of a steering wheel [5].

$$22 \cdot k \cdot N \geq 50 \qquad \text{Eq. (B.3)}$$

To minimize the distance from the center of the servo that the force is applied, and ultimately the torque, the servo needs to rotate a full 180 degrees to open the clamp. This gives the required value for r:

$$r = \frac{40}{\pi} = 12.73mm \qquad \text{Eq. (B.4)}$$

The value for k was observed to be 0.53N/mm using a known mass of 500g to stretch the spring and callipers to measure the change in length. This means that N = 4 to satisfy (B.2). Maximum torque values for the servo, and the maximum force of each spring were resolved.

TABLE B.2. SIGNIFICANT VALUES

ID.	**Description.**	**Value.**
Critical Values[a].		
V1.	Minimum force output of the clamp/springs for all wheel sizes.	$50N$
V2.	Maximum torque output required of the servo by the design in order to output	$116N \cdot cm$[b]

	required force.	
Significant Design Specifications.		
V3.	FoS of HS-805BB servo motor.	$\frac{202.12}{116} = 1.74 > 1.5$[c]
V4.	Spring constant (k).	$0.53 \frac{N}{mm}$
V5.	Force exerted by one spring when stretched to 40mm.	$21.2N$

[a] Values dictating bound(s) on a "passed" test protocol (see Table 1).
[b] Calculated from Eq. (B.1) where k = 0.53, N = 4, and r = 12.73mm.
[c] 202.12 N·cm is the maximum torque of the HS-805BB [9].

Appendix C: FEA Analysis

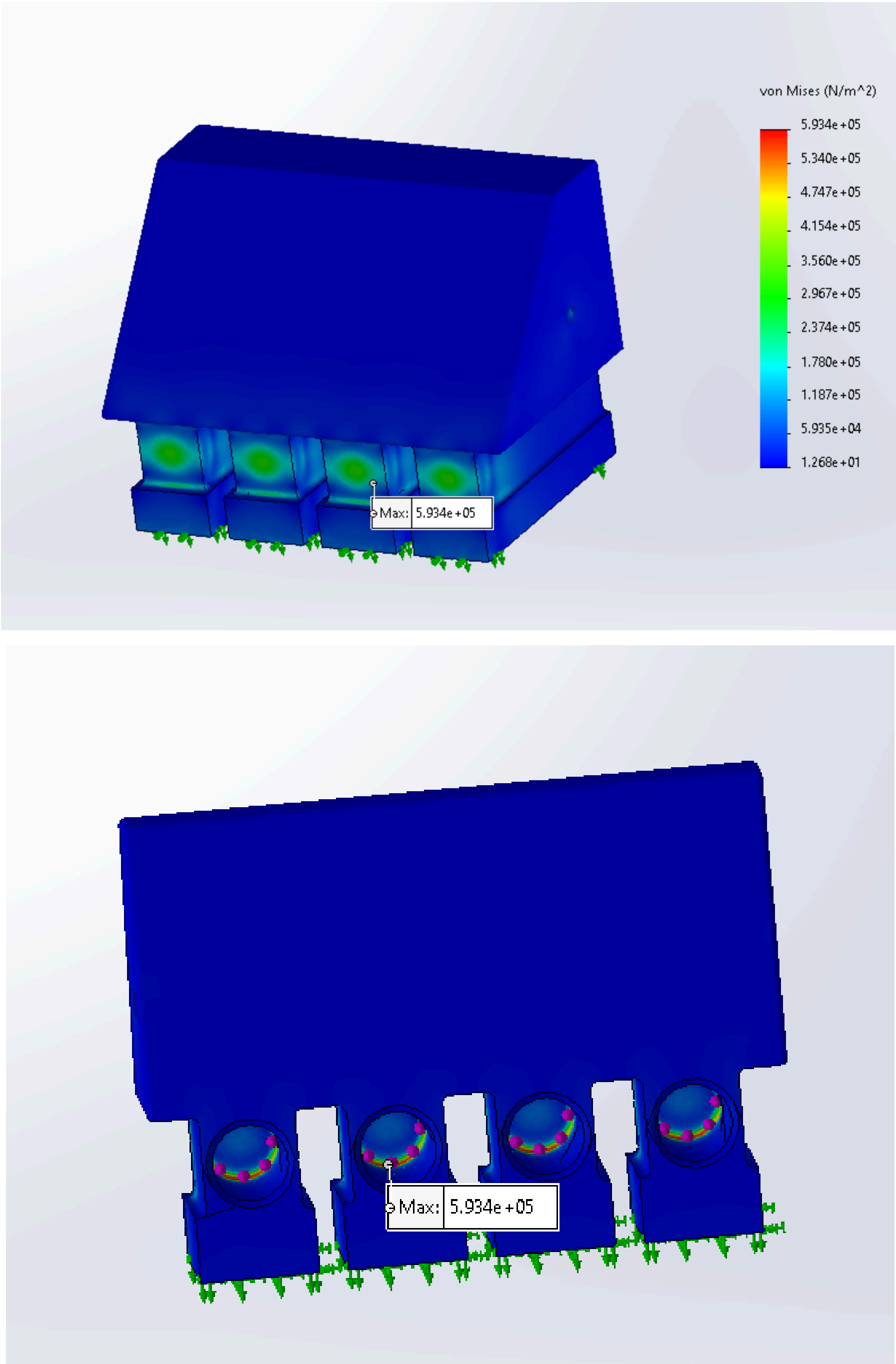

Fig. C.1. FEA analysis on the preliminary design sliding block.
Equal forces of 21.2N were applied at the spring holes, and the part was not permitted to move up or down at its feet, and not allowed to move in any direction at the hole where the string threads through.

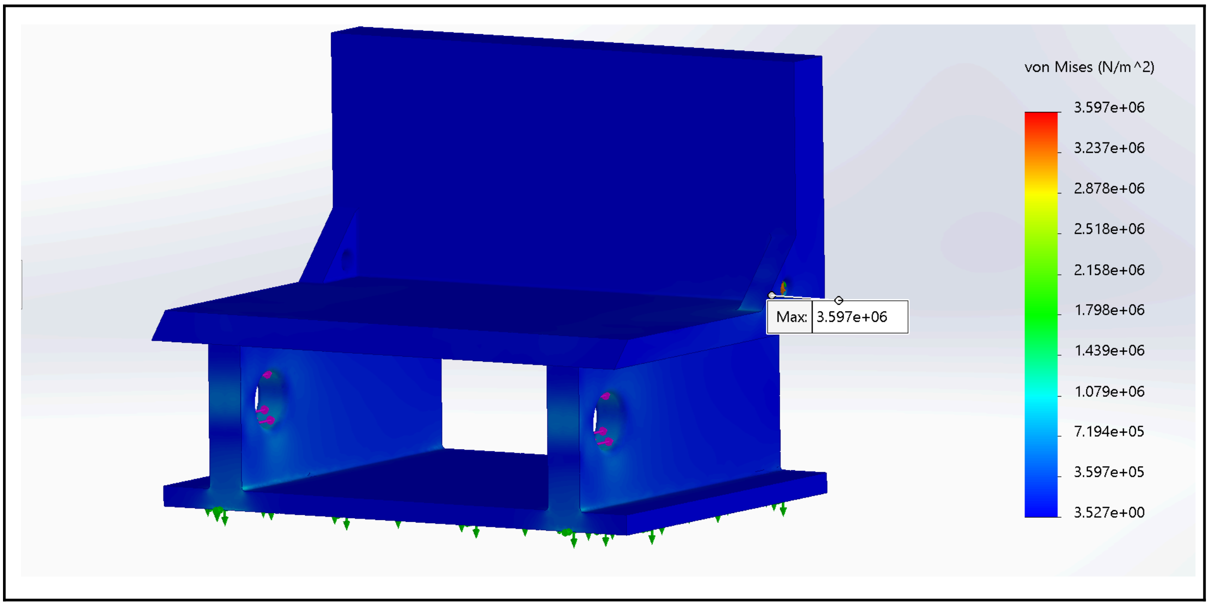

Fig. C.2. FEA analysis on the final design sliding block.
Equal forces of 42.4N were applied at the bolt holes. The part was also not permitted to move up or down at its feet, and not allowed to move in any direction at the hole where the string threads through.

Appendix D: Circuit Simulation and Bode Plots

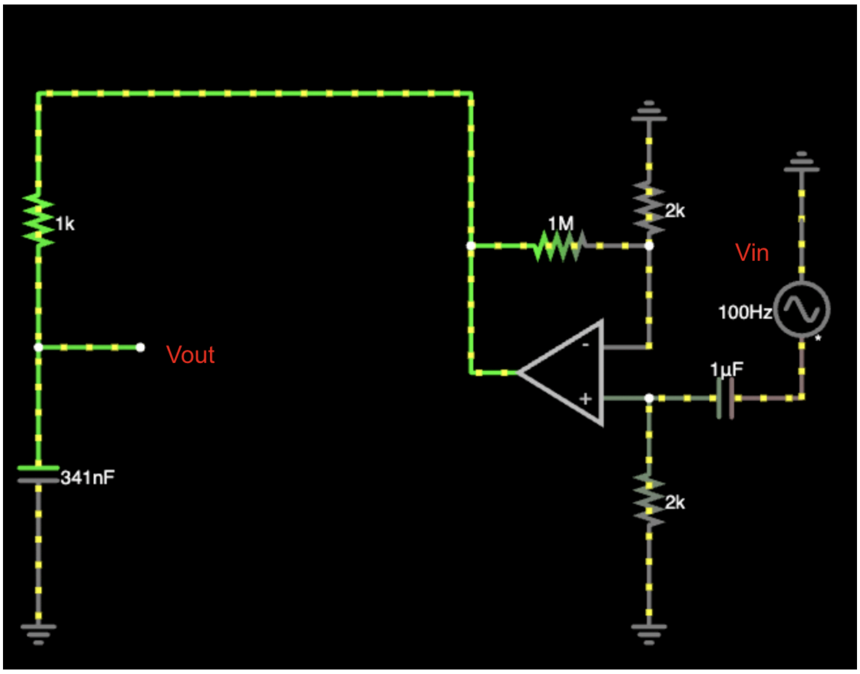

Fig. D.1. Falstad simulation of EMG circuit [8].

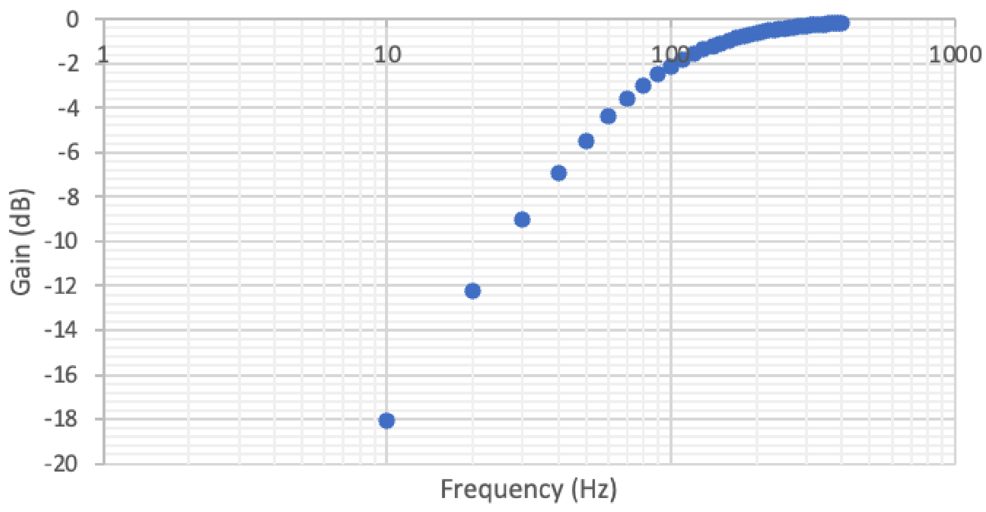

Fig. D.2. Theoretical bode plot of high pass filter.

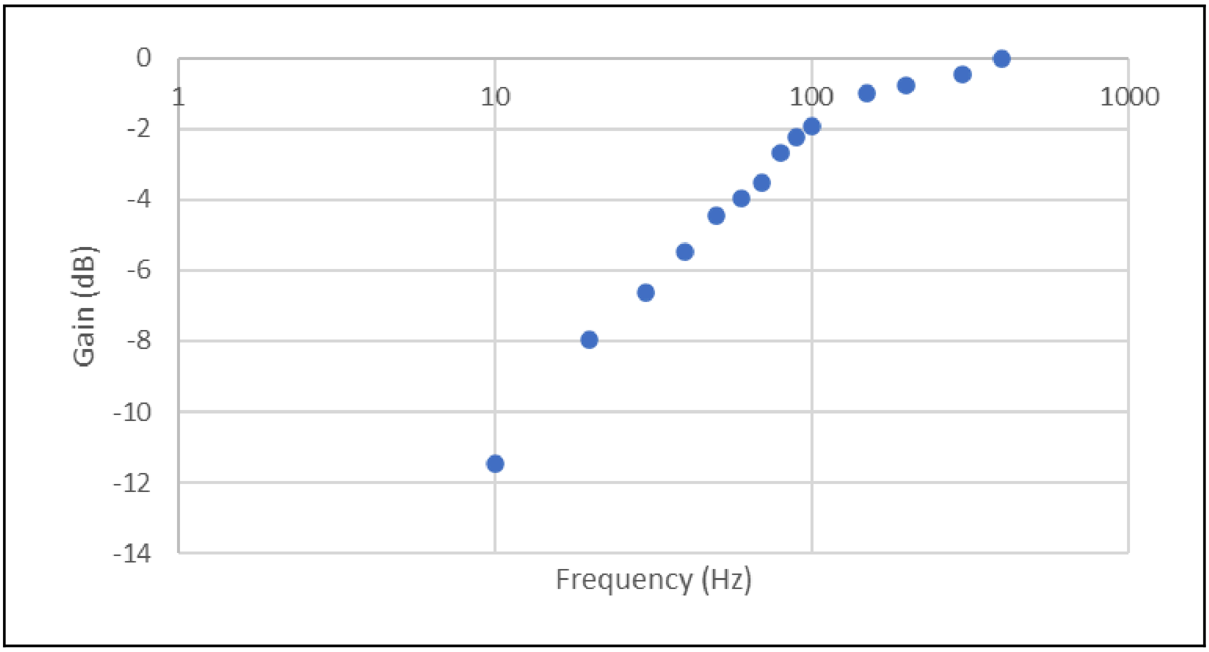

Fig. D.3. Experimental bode plot of high pass filter.

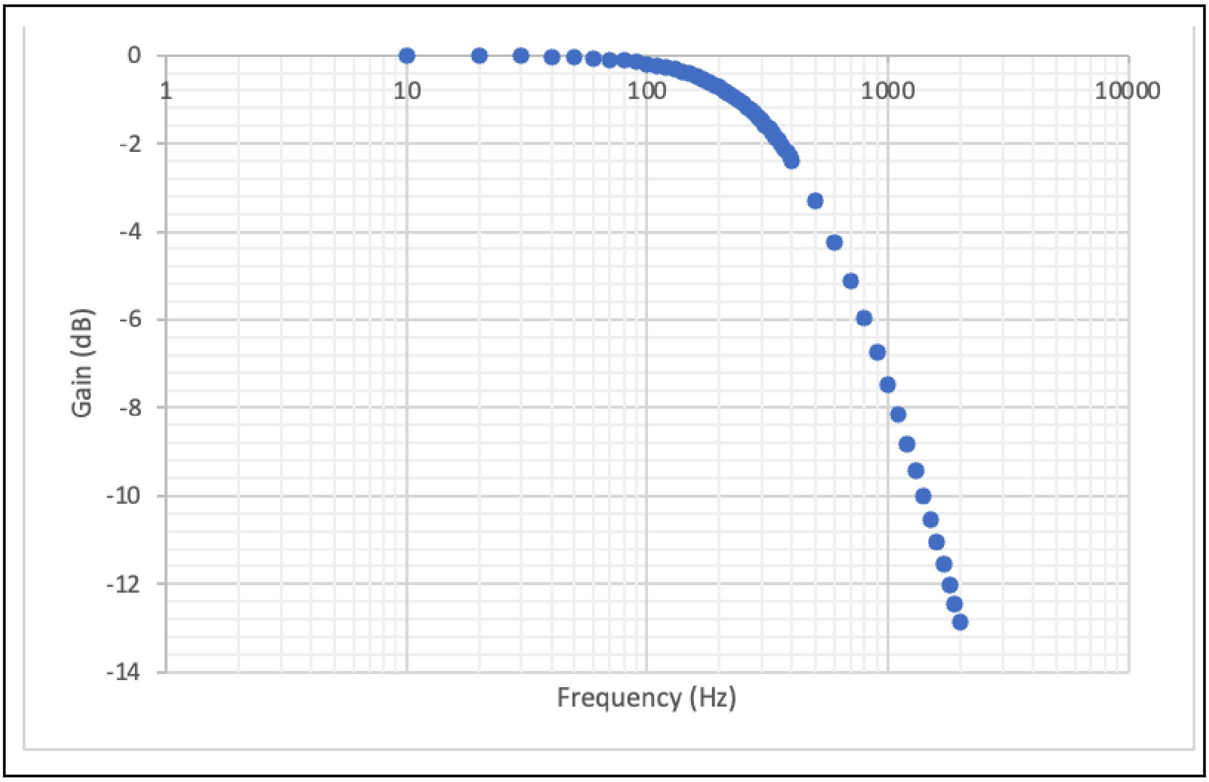

Fig. D.4. Theoretical bode plot of low pass filter.

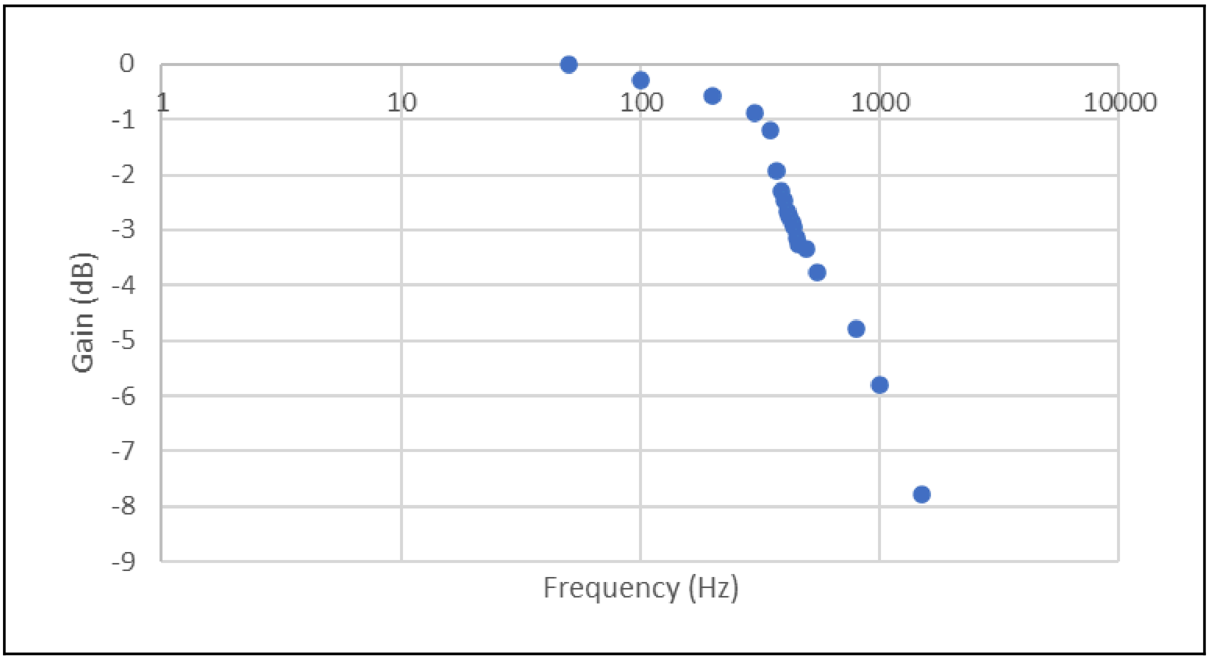

Fig. D.5. Experimental bode plot of low pass filter.

Appendix E: Code

```
// Aidan Kirwin & Connor Irvine, ©2023
#include <Servo.h>

// Declare signal input pin
int emgSignal = A0;

class Movement
{
  public:
  bool move;
  Servo Servo1;
  int servoPin;
  float threshold;
  Movement();
  void Update(float RMS);
};

Movement::Movement()
{
  move = false;
  servoPin = 3;
  threshold = 42;
}

void Movement::Update(float RMS)
{
  // Binary vals
  if(RMS >= threshold) move = true;
  else
  {
    move = false;
  }
}

class Time
{
  public:
  static float time;
  static float previousTime;
  void Update();
};

float Time::time = 0;
float Time::previousTime = 0;

void Time::Update()
{
  Time::previousTime = time;
  Time::time = millis();
```

```
}

class Derivative
{
  public:
  float derivative;
  int voltage;
  int previousVoltage;
  float Update(int value);
};

float Derivative::Update(int value)
{
  voltage = value;
  if(Time::time == 0) previousVoltage = voltage;

  float interval = Time::time - Time::previousTime;
  derivative = abs((voltage - previousVoltage) / interval);

  previousVoltage = voltage;
  return derivative;
}

class RMS
{
  public:
  RMS();
  float Update(float val);
  private:
  float *derivatives;
  float lastVal;
  int size;
  const int n = 30;
};

RMS::RMS()
{
  size = 0;
  derivatives = new float[n];
  lastVal = 0;
}

float RMS::Update(float val)
{
  if(size < n)
  {
      derivatives[size] = val;
      size++;
      return lastVal;
  }
```

```

  float sum = 0;
  for(int i = 0; i < n; i++)
  {
    sum+=pow(derivatives[i], 2);
  }

  float mean = sum / (float)n;
  float RMS = sqrt(mean);
  lastVal = RMS;

  size = 0;

  return RMS;
}

Time m_time;
Derivative m_derivative;
RMS m_RMS;
Movement m_move;

void setup()
{
  // Attach servo object to the pin
  m_move.Servo1.attach(m_move.servoPin);
  // Set baud rate (data rate in bits per sec)
  Serial.begin(9600);
}

void loop()
{
  // Update time
  m_time.Update();

  // Get current sampled signal val
  int val = analogRead(emgSignal);

  // Take derivative
  float derivative = m_derivative.Update(val);

  // Take RMS
  float RMS = m_RMS.Update(derivative);

  // Check if servo should move
  m_move.Update(RMS);

  // Move servo
  if(m_move.move == true)
  {
    m_move.Servo1.write(0);
```

```
  }
  else
  {
    m_move.Servo1.write(180);
  }
}
```