Individual Analysis

Inna Quiambao

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Biomechatronic Hip Exoskeleton Team

1. Introduction

I am a part of the Biomechatronics Hip Exoskeleton Team for the Northern Arizona University Capstone course. The goal of our project is to create a hip exoskeleton that will ideally be used for children with cerebral palsy. The team is also working in conjunction with the Biomechatronics Lab at NAU, our client specifically being Leah Liebelt.

Overall, the exoskeleton needs to be able to actuate movement in extension and in flexion while staying passive in all other degrees of motion. It also needs to be powered for about two hours at a time. The problem that is going to be analyzed in this paper is figuring out the type of battery needed for the exoskeleton. This means understanding the power draw of the motor and analyzing the current flowing through this circuit. Though, our team has not picked a specific motor yet. As a result, my goal turned into trying to figure out a way to analyze any kind of motor to view the torque and speed outputs, and the current supply that would be needed from the battery.

2. Assumptions

There were a couple assumptions made before the actual calculations began. First, we used a EC-4pole Maxon motor as a basis for these calculations. This motor was chosen because it is the one that used in the Biomechatronics Lab at NAU for their larger motor assembly design [1]. The values of the motor will be shown in the table below.

Table 1: Motor Properties [2]

Motor	Nominal Voltage (V)	Power (W)	Nominal Speed (RPM)	Nominal Torque (mN-m)	Efficiency (%)
EC-4pole 22	24	120	15800	54.5	89

The only value that isn't used in this table will be the power. This is because we calculate the new power output that results from a gear reduction. A range of gear reductions will be used to calculate different outputs. The lower bound was decided to be 111:1, since it was used to Lerner's ankle exoskeleton [1]. The upper bound was estimated to be 327:1 which was found by using the formula below.

$$r = \frac{T_{out}}{T_{in}} \text{ [3]}$$

This is where r is equal to the gear reduction ratio, T_{out} is torque output, and T_{in} is torque input. The value for torque output was 17.85 N-m, which was found by multiplying the required torque outputs found by the Army Research Laboratory by 25% of the average body mass of a person (62 kg) [4]. Torque input was 54.5 mN-m. This formula will be covered again in Section 3.

There are also going to be four FSR sensors that sense the force it takes actuate movement in extension and flexion. These act like resistors in a circuit that will change resistance depending on the amount of force pressed against them. Resistance ranged from 100 kΩ for less force, to 200Ω for max force [5]. Also, in future equations a 10 kΩ pull-down resistor will be used which was recommended by Adafruit Learning System [5].

3. Defining Variables and Equations

The following sections will go over specific formulas for certain parts of the system. Variables will also be defined throughout this report.

3.1 FSR Equation

To easily measure the results from an FSR sensor companies recommend connecting one end to the power and the other to a pull-down resistor to ground [5]. This is because you will be able to see the voltage increase across the resistor has it is pressed. Though, I did not want to check this to read the results of the FSR. I believed it was important to check if the voltage output would be high enough to effect what battery would be needed. As a result, I used the formula given by Adafruit Learning to calculate the output voltage.

$$Equation\ 1: V_{out} = V_s * \left(\frac{R}{R+FSR}\right)\ [5]$$

The value V_{out} represent the output voltage. V_s is the voltage source which is 24 V. R is the drop down resistor which is 10 kΩ. Lastly, FSR is the range of values from 200 Ω to 100 kΩ. All assumed values and their reasoning were covered in Section 2.

3.2 Power Outputs and Supplied Current Equations

To cover the equations used to find the torque output, speed output, and total current supplied by the battery, they will be covered in the order they were used in. This is for ease of reading, and also referencing them in the later code will be simpler.

First the gearbox ratio equations will be used. Gearbox reduction is used to increase the torque output of a motor and to decrease the speed. This is beneficial to the team because we need a specific torque to be able to actuate movement in the hip, but this value varies between a child and an adult. The two gearbox reduction equations used will be shown below.

$$Equation\ 2: T_{out} = T_{in} * r\ (Nm)\ [3]$$

$$Equation\ 3: N_{out} = \frac{N_{in}}{r}\ (RPM)\ [3]$$

The values for Equation 2 were covered in Section 2. N_{out} is the speed output of the motor in RPM. N_{in} is the speed input of the motor which is 15800 RPM. Lastly, r is the gear reduction ratio.

To find the power output of the motor, the results from Equation 2 and Equation 3 will be multiplied. First, N_{out} needs to be converted from RPM to rad/sec,

$$Equation\ 4{:}\ \omega_{out} = N_{out} * \frac{2\pi}{60}$$

$$Equation\ 5{:}\ P_{out} = T_{out} * \omega_{out}\ (W)\ [6]$$

Once you convert N_{out} to ω_{out}, which is the rotational speed in rad/sec, that value will be used to find P_{out} in Equation 5. This is the power output of the motor in watts. Since the power output has been found, the efficiency of the motor can be used to figure out the electrical power going into the motor.

$$Equation\ 6{:}\ P_{in} = \frac{P_{out}}{\eta}$$

The P_{in} represents the electrical power input into the motor, while η represents the efficiency of the motor. This value can be used to find out the value the current going through one motor.

$$Equation\ 7{:}\ I = \frac{P_{in}}{V_m}\ (A)\ [6]$$

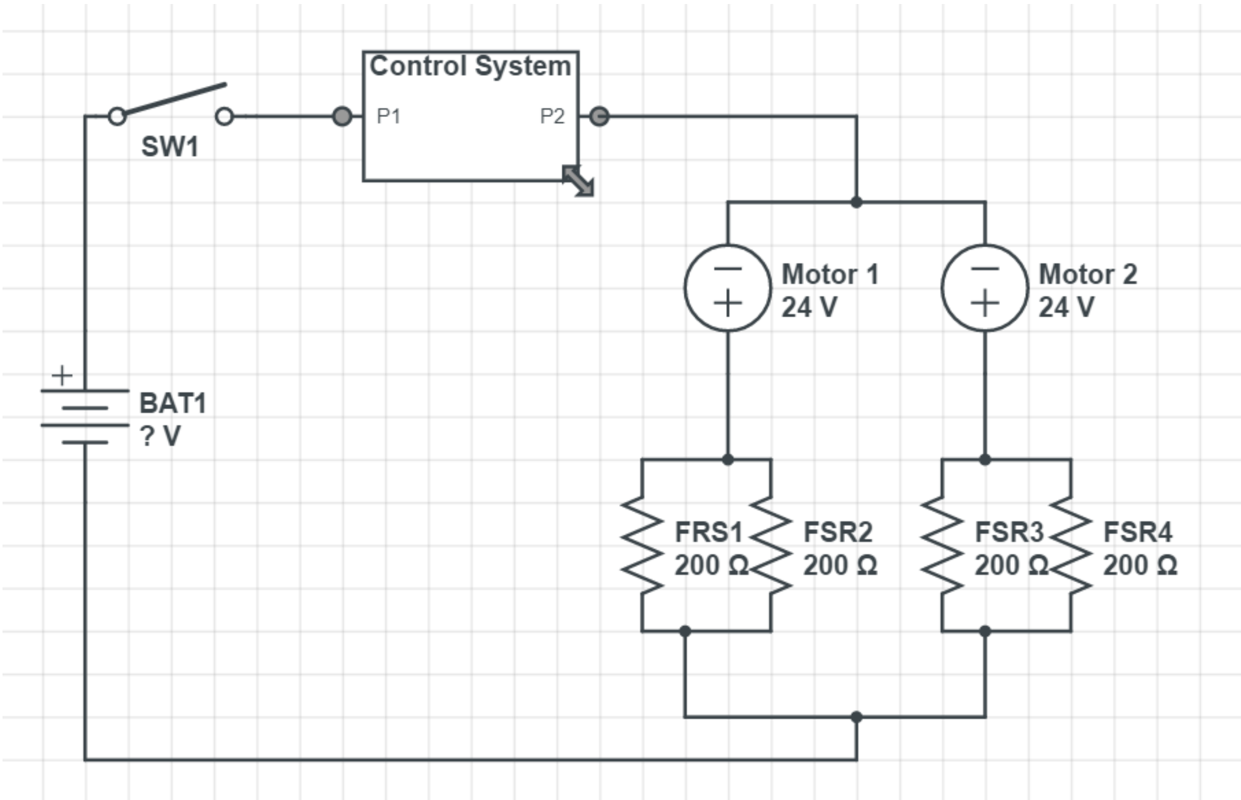
The value I represents the current going through one motor in the circuit, and V_m is the voltage of the motor which is 24 V. To find the current that needs to be supplied by the battery, the value I is multiplied by two. This is because there are two motors in the circuit, which means I amount of current needs to be supplied to each once.

4. Schematics and Flowchart of Code

To understand the flow of the current through the circuit, it is imperative to create a circuit diagram. Throughout this analysis, two were created, and it will be covered why one was used over the other. Also, flowcharts of the code will be provided to accompany the diagram they are related to.

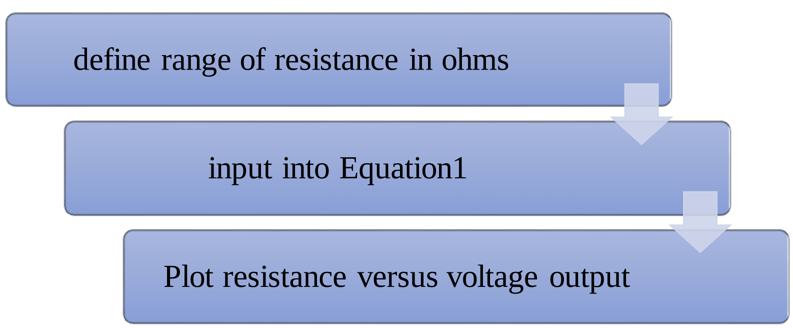
This first figure is of the circuit diagram featuring the FRS sensors. Since there would be four of them within the system, I wanted to check if there would be any voltage drop between the resistors.

Figure 1 Circuit Diagram A featuring FRS Sensors



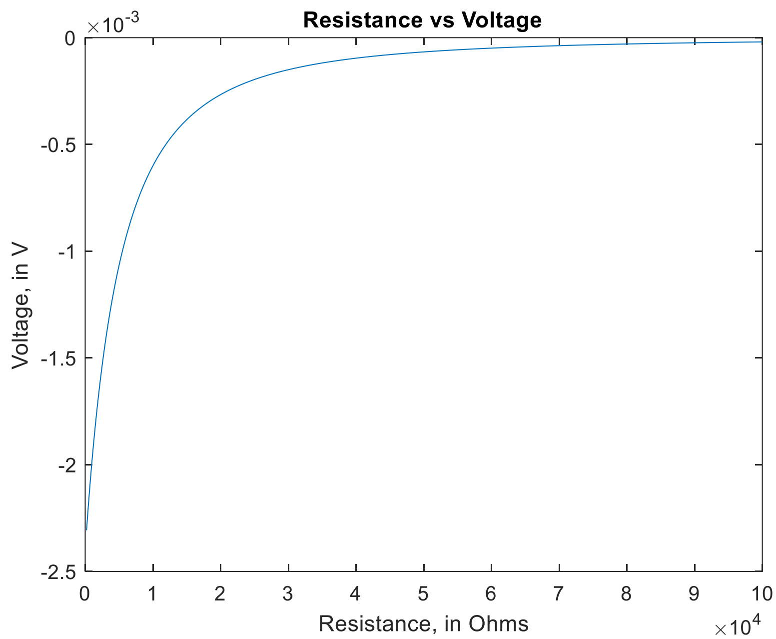
To check the values of the voltage output of the FRS sensors, Equation 1 was used in a MATLAB code. This code took different resistance values ranging from 200Ω to 100kΩ to check the voltage drop.

Figure 2 Flowchart of FRS Code



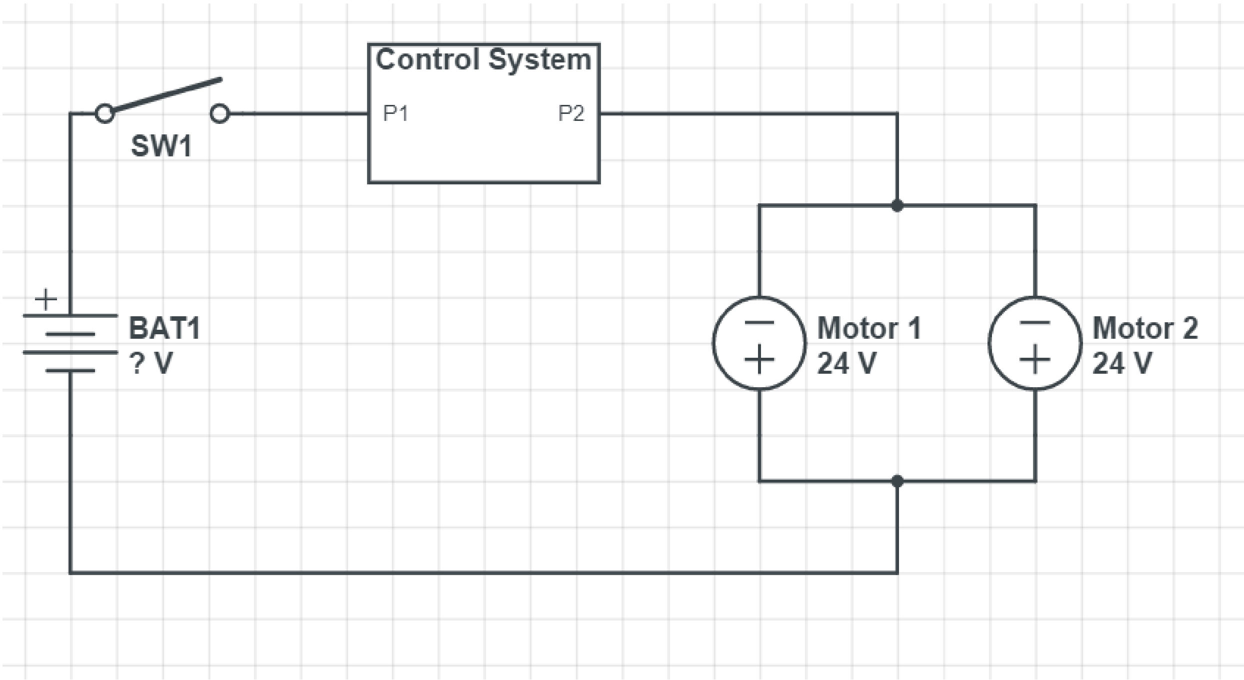
The resulting plot of the code of the code will be shown below in Figure 3.

Figure 3 Resulting FSR Plot



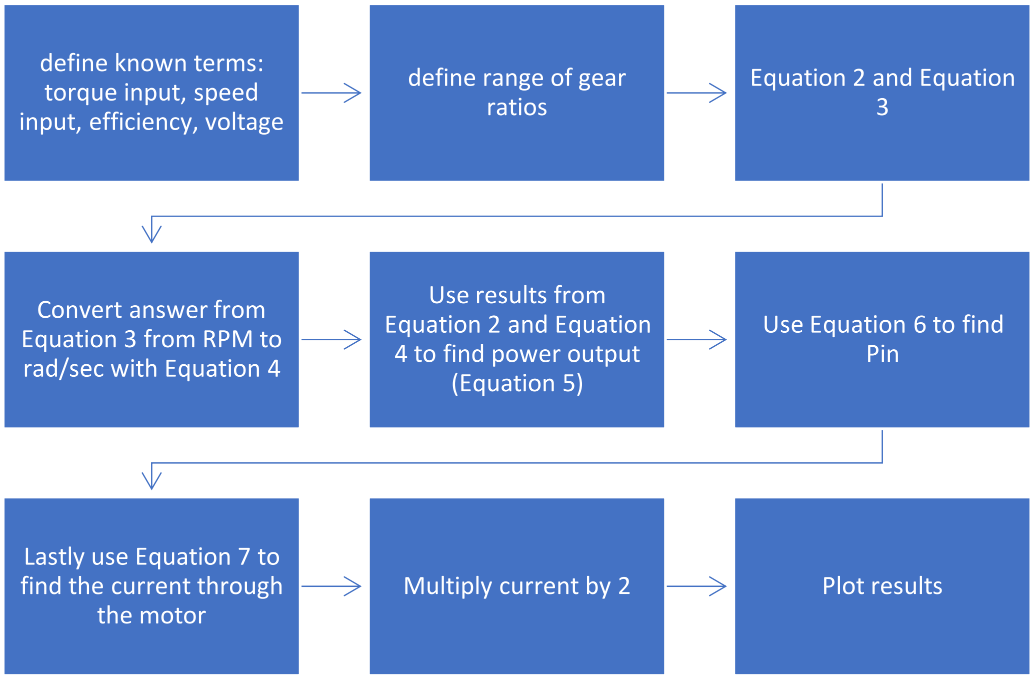
This shows that the voltage drops across the FRS resistors were small, and as a result could be neglected. The next circuit diagram is the one used for the final MATLAB analysis.

Figure 4 Final Circuit



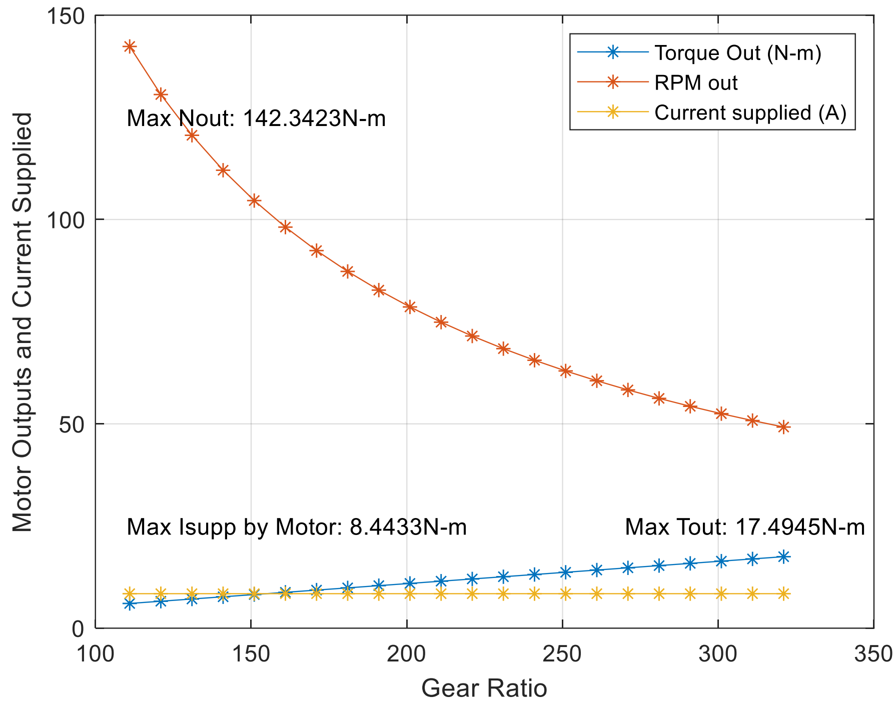
This circuit shows that we can assume the battery has to be a 24 V battery. According to the rules regarding voltages in parallel, the voltage drop across each node has to be equal **[6]**. Now I can used this diagram to generate the code needed to analyze the torque output, speed output, and the current supplied by the battery. To show the flow of the code, a flow chart will be created showing the order of equations used and how they relate to one another.

Figure 5 Flowchart of Analysis



The full code can be referenced in Appendix A. The resulting plot can be referenced below.

Figure 6 Final Plots



Overall, the results are accurate to what a gear reduction would cause. The RPM out decreased as the gear ratio increased, and the torque out increased. Though, the current stayed the same throughout the changing gear reductions.

6. Results and How It Will Influence Project

These results show that if we use two 24 V motors, we would need a 24 V battery that can supply 8 A of current. We have flexibility on how we create the 8 A of current, such as we can mix battery packs together, or use multiple rechargeable batteries. Overall, this analysis showed that whatever gear reduction we pick will not change the current supplied. Which makes sense with how the equations are all related. Overall, the most important part of picking the right battery will be what kind of motor we pick towards the end of our prototyping. Once we pick a specific motor, this analysis can be used again to figure out the exact current needed and how gear reduction will affect it.

References

[1] Z. F. Lerner, G. M. Gasparri, M. O. Blair, J. L. Lawson, J. Luque, T. A. harvey and A. T. Lerner, "An Untethered Ankle Exoskeleton Improves Walking Economy in a Pilot Study of Individuals With Cerebral Palsy," *IEEE Transactions on Neural Systems and Rehabilitation Engineering,* pp. 1985-1993, 2018.

[2] Maxon, "Maxon Motors," 2019. [Online]. Available: https://www.maxongroup.com/maxon/view/category/motor?etcc_cu=onsite&etcc_med_onsite=Product&etcc_cmp_onsite=EC-4pole+Program&etcc_plc=product_overview_brushlessdcmotors_ec4pole&etcc_var=%5bcom%5d%23en%23_d_&target=filter&filterCategory=ec4pole.

[3] Engineering Toolbox, "Gear Reducing Formulas," [Online]. Available: https://www.engineeringtoolbox.com/gear-output-torque-speed-horsepower-d_1691.html.

[4] H. P. Crowell III, A. C. Boynton and M. Mungiole, "Exoskeleton Power and Torque Requirements Based on Human Biomechanics," 2002.

[5] Adafruit Learning System, "Force Sensitive Resistor (FSR)," 2018.

[6] C. A. Gross and T. A. Roppel, Fundamentals of Electrical Engineering, CRC Press LLC, 2012.

Appendix:

Appendix A:

```
clc
clear
%checking voltage drop across resistors
fsr = 200:10:100*10^3; %in ohms
V = (24*((10*10^3)./((10*10^3)+fsr))./(1-((10*10^3)+fsr)));
...
    %voltage divider formula
figure
plot(fsr,V)
xlabel('Resistance, in Ohms')
ylabel('Voltage, in V')
title('Resistance vs Voltage')
%results show that it is very small so we can neglect it

Tin = 0.0545;%Nm
Nin = 15800; %rpm
eff = 0.89;
V = 24; %V

r = 111:10:327; %different gear reduction, read as 1:111,
1:327
Tout = Tin.*r; %Torque Output in N-m
Nout = Nin./r;%Speed of motor output in RPM
wout = Nout.*((2*pi)/60); %Converting RPM to rad/s
Pout = Tout.*wout; %calculating Power output of motore (W)
Pin = Pout./eff; %Electrical power into motor (W)
I = Pin/V; %Current (Amperes) through each motor
Isupp= 2.*I; %Total supplied current

figure %Plotting gear ratio vs Torque output, RPM Output,
and
       %Current Supplied by Battery
plot(r,Tout,'-*','MarkerIndices',1:1:length(Tout));
maxT = max(Tout);
txt = ['Max Tout: ' num2str(maxT) 'N-m'];
text(270,25,txt)
hold on
plot(r, Nout,'-*','MarkerIndices',1:1:length(Nout));
maxN = max(Nout);
txt = ['Max Nout: ' num2str(maxN) 'N-m'];
```

```
text(110,125,txt)
hold on
plot(r,Isupp,'-*','MarkerIndices',1:1:length(Isupp));
maxI = max(Isupp);
txt = ['Max Isupp by Motor: ' num2str(maxI) 'N-m'];
text(110,25,txt)
xlabel('Gear Ratio')
ylabel('Motor Outputs and Current Supplied')
legend('Torque Out (N-m)','RPM out', 'Current supplied
(A)')
grid on
```