Design Showcase 2

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Summary of Problem Space

Situation of Concern

There are several groups of people who use wheelchairs due to lower limb mobility issues including those with a spinal cord injury, spinal nerve, and cauda equina issues, and lower limb amputations [1]. This wheelchair use makes it more challenging for these individuals to participate in exercise and other types of physical activity leading to muscular and aerobic deconditioning, weight gain, and weight-associated medical issues [1], [2]. These medical issues can include obesity, diabetes mellitus, hypertension, cardiovascular disease, osteoporosis, and osteoarthritis [1], [2]. The WHO recommended exercise level is 150 minutes per week of moderate intensity aerobic activity and muscle-strengthening activities twice per week [3]. Regardless of the recommended exercise level, wheelchair users face many barriers to exercise participation. Some options for exercise include wheelchair propulsion, treadmill or wheelchair rollers, cyclical arm ergometry, accessible rowing machine, wheelchair sports, swimming, free weights, weight machines, and elastic bands [2], [4]. Many of these options are specialized and only available in a limited number of gym facilities, requiring a gym membership and potentially driving a long distance from home [5]. Arm ergometers range in price from $90 to $225 but are often perceived as boring by users, and it can be challenging to reach a high heart rate using this propulsion-like motion [4], [6]. Wheelchair treadmills or rollers can cost over $1,000 for a basic model [7]. Therefore, there is a need to design a device to be used by individuals with loss or impairment of lower body function who use a wheelchair, to track their daily activity and motivate them to be active that provides quantifiable feedback regarding their activity levels. This situation of Concern is a modified version of [8].

Key Requirements and Constraints

- Must accurately track data
    - Measured parameters: rotations, distance in m
    - Metric: 10% error margin
- Must be adjustable
    - Measured parameters: cm
    - Metric: minimum 7 cm of adjustability
- Must not impede wheelchair movement
    - Measured parameters: Change in speed and angle
    - Critical value: maximum margin of ±0.2 km/h difference in speed, and ±3° deviation in angle after the device is installed

Basic Functions

The product is a fitness tracker for wheelchair users which is capable of measuring and tracking the user’s movement and fitness data, such as wheel rotations, pushes, and distance travelled. The product also has a social aspect, meaning that tracked data can be shared and compared with other users. These two functions enable the third function, which is that the device helps motivate users to exercise. Viewing one’s own fitness data aids users in staying consistent with their exercise, and the social aspect introduces a competitive aspect for further motivation [9].

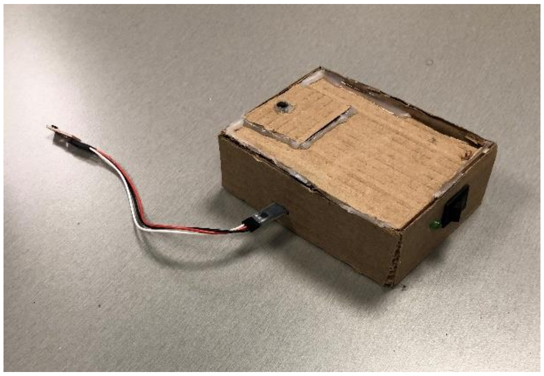
Solutions and Prototypes

The chosen solution (figure 1) is a wheelchair-mounted device containing several sensors and a wheel mounted magnet necessary to detect wheel rotation. This device sends movement data to an accompanying mobile phone application. The application receives the data and presents it in a visually appealing manner to help motivate users to reach their goals. Additionally, the application contains social features that utilize competition with friends to further motivate users to exercise. From a technical perspective, a non-latching hall-effect sensor is utilized to detect wheel rotation, and a 3-axis accelerometer and gyroscope is used for detecting angle of incline and acceleration. The design shown illustrates how the non-latching hall-effect sensor (affixed to the end of the movable arm) must be positioned to detect wheel rotation, while the accelerometer/gyroscope is integrated directly into the circuit within the body of the device. The current design is made of ABS plastic – a durable plastic with high resistance to impacts that is well suited for common manufacturing processes (injection molding and 3D printing) [10].

Figure 1: Sketch of the final design

The low-fidelity prototype (figure 2, 3) is constructed of cardboard as physical durability is not required for testing, however the circuitry within (figure 3) is very similar to the high-fidelity design. A SparkFun Infrared Line Sensor [11] is used to detect rotation instead of a hall-effect sensor due to easy access for the team at the time of constructing the prototype. The use of the line sensor also requires an additional cardboard tab attached to one of the spokes of the wheelchair so that a single reading is taken every wheel rotation. Furthermore, a Pololu LSM6DS33 3D accelerometer and gyroscope [12] is used for gathering the accelerometer data similarly to how it is collected in the solution design. The sensors are connected to a miniature breadboard which is in turn wired to an Arduino Uno microcontroller [13] which interprets, post-processes, and presents the data when a push-button is pressed. Additionally, the prototype contains a toggle switch to control power to the circuit, as well as an indicator light. The total cost of the circuitry materials used in the prototype is ~60$ including the cost for wiring. While the testing of this device is focused on the accuracy of the rotation tracking, the prototype has a larger range of functionality. The sensors gather acceleration and wheel rotation data and use this data to present the number of wheel rotations, elapsed time from when the device is powered on, amount of distance travelled, and the number of times the wheelchair is pushed. The number of wheel rotations is counted directly by the line sensor, while the timer is run from the Arduino. The distance is calculated by taking a user-entered wheel diameter, calculating the circumference from said diameter and multiplying the circumference by the number of wheel rotations. Lastly, the number of pushes is counted by looking for large spikes in acceleration in the direction of wheelchair movement (x-axis during testing) and counting large jumps in acceleration as a push.

Figure 2: Exterior view of prototype



Looking towards the future, there are several changes needed to take the prototype to higher-fidelity stages. First and foremost, the cardboard construction will be replaced with plastic components as shown in the solution sketch. Furthermore, additional functionality will be added to the device, such as Bluetooth connectivity to allow the device to connect to the app shown in the solution. Lastly, the functionality of the sensors will be expanded and made more robust. This will include the addition of stopwatch features, active versus elapsed time features, average and max speed calculations, and the patching of some small bugs revealed in the prototype such as inaccurate fluctuations in the acceleration data. These bugs can likely be addressed through the addition of low pass filters or other data post-processing measures that more effectively smooth data than the current prototype.

Engineering Analysis

As our device is a sensor which is permanently affixed to the wheelchair after installation, it is essential that the device has no negative impact on the mobility of the wheelchair. Therefore, the second constraint, 'must not impede wheelchair movement,' was chosen for the engineering analysis. This constraint is measured by the speed of the wheelchair and the angle of deviation from a straight line when in use. However, this was then iterated upon to be better analyzed. The modified constraint is measured by external force acting upon the wheelchair, which must not exceed the critical value of one newton. The value of this constraint stems from the importance of the device not negatively impacting wheelchair movement. Meaning, if the functionality of the wheelchair is negatively impacted by our design, the success of our product becomes redundant as the device will not be able to be effectively used.

Given that the evaluation is focused on the forces exerted by the device on the wheelchair, this is a statics-based analysis [14]. Specifically, this is a three-dimensional equilibrium problem because the bodies must be at rest to properly calculate the effects of the device.

The overall goal of the analysis is to determine the force of the sensor on the wheelchair, or the reactions at the point of contact. This is represented on the free body diagram as point A, represented in figure 4. To determine our given data, SOLIDWORKS software was used to build a depiction of our prototype. This was then used to determine the dimensions of our device as well as the approximate weight, which is 450 grams. Notably, all dimensions are displayed on the front and side view diagrams of our sensor, as seen in figure 5. Preliminary assumptions were defined as followed; gravity is a force acting down with an acceleration of 9.81 m/s^2 and the sensor is a rigid body, meaning it does not deform. Additionally, point A is a fixed joint attached to the wheelchair, giving it forces in the x, y, and z directions. Finally, the center of mass of our device is assumed to be the exact center of the object, accounting for all directions.

After completing this approach, 3D equilibrium was applied to the free body diagram to begin the calculations. Firstly, the sum of the forces is set to zero to determine the individual forces of A. This process is repeated for each of the three directions. Secondly, with the forces of A, and the dimensions of the device, the moment about A is calculated using the cross product. The result of this is a force of -8.29×10^{-2} Nm in the x direction and 2.98×10^{-1} Nm in the z direction. These calculations are clearly illustrated in figure 6.

Evidently, the forces of our design on the wheelchair are extremely small. Notably, they are safely under the critical value. Furthermore, knowing that the average wheelchair manual wheelchair weighs between 6.8 to 27.2 kilograms on average, the minimum force required to move a wheelchair would be around 66 newtons [15]. Hence, the force of our device on the wheelchair is negligible. This means that the current design concept requires no revision regarding our engineering analysis and further testing could be conducted.

Testing

The prototype was created at low fidelity to evaluate the requirement that the device must accurately track data. This requirement is assessed through sensor-based testing. The metric that is focused on tracking is wheel rotations. By comparing the wheel rotations tracked by the device versus manually counted rotations, the interference of the device is realized. This metric is chosen as wheel rotation is utilized when calculating distance travelled, and rotations per minute. Due to this being the first testing on the device, a larger critical value of a 10% error margin was allocated. In the future, this margin would be reduced in accordance with testing capacities. The tested requirement is outlined in the table below (see table 1).

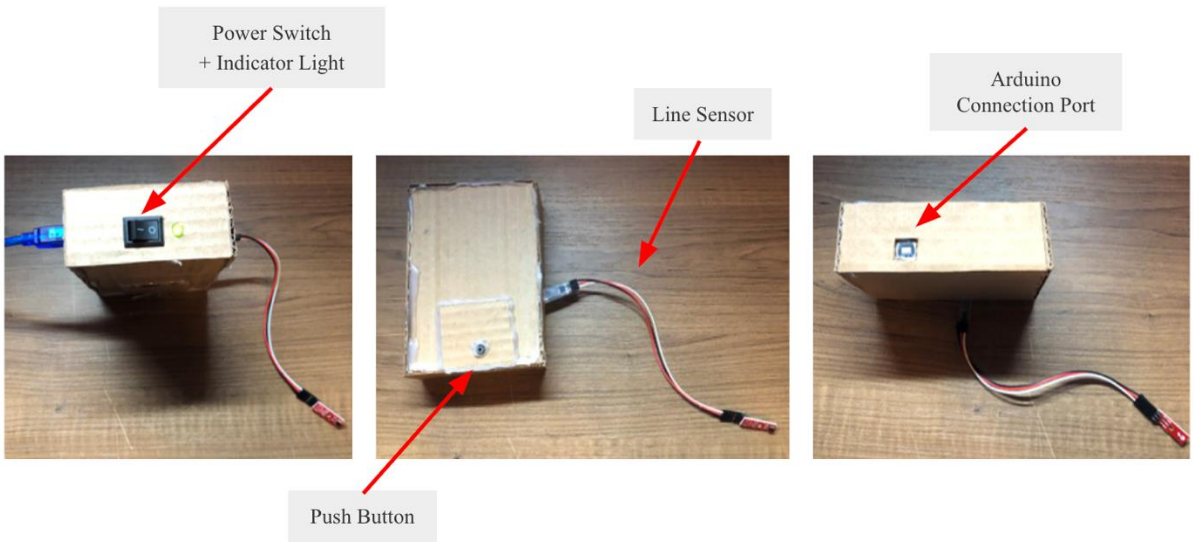
Table 1: Requirement 1

Description	**Measured Parameter**	**Testing or Evaluation Protocol**	**Critical Value**
R1. Must accurately track data	Rotations/min	Track manually and compare results with received data.	10% error margin

Testing Protocol:

A line sensor is also utilized and hangs outside of the box (see figure 3). The device contains 3-axis accelerometer and gyroscope, and a line sensor, which are packaged within a box constructed using cardboard and hot glue. Cardboard was chosen as it is stiff enough to protect the hardware and a cheap material. The box is attached underneath the wheelchair's armrest using tape, while the line sensor is attached with tape behind the wheel. Feedback from the device is sent from the sensors through a physical wire which plugs into the Arduino connection port (on the device) and the computer. Due to the length constraint of this wire, the user tester has the computer on their lap. This is also the reasoning behind the location of the sensor box. The armrest is close to the user and an easy location to fasten the device to the wheelchair.

Figure 3: Exterior view of tracking device



The line sensor is used like a proximity sensor, therefore any time something passes over the sensor is tripped. This ability is utilized during testing by affixing a piece of cardboard on the rim of the wheel so that every time the wheel made a full rotation the sensor would be tipped by the protruding material. This allows the Arduino to recognize a rotation is completed, and therefore a rotation is counted by the device. The line sensor accuracy has an error of up to 3mm which is acceptable to track wheel rotations as the width of the cardboard on the rim is much larger. Prior to testing, the device is calibrated to adjust the line sensor sensitivity to be triggered. To prepare for use the device is turned on using the power switch (see figure 3 above). Additionally, prior to testing the tracker is calibrated to ensure the Arduino accurately counts wheel rotation.

Testing consists of three trials and three participants. Each trial starts with the testing user sitting in the wheelchair and starting the program on the computer on their lap. The user then begins to move the wheelchair by pushing on the wheels. This first participant continues to push until five wheel-rotations are reached. This specific distance was chosen due to the space constraints of the testing environment. During the test, a second participant manually counts the number of times that the tape passes the sensor, representing the number of wheel rotations. After five rotations are met, the push button (see figure 3 above) is pushed, signalling to the Arduino to print out data tracked; this tells the code that the trial is over, and that the intake of data can be stopped. The information printed is already run through programmed formulas to find certain metrics. The rotations that are counted by the tracker and counted manually by the second participant are then recorded by the third participant. These numbers are then compared for tracker accuracy.

Testing Data:

Table 2: Number of wheel rotations counted during manual and sensor testing.

Attempt #	Number of Wheel Rotations Counted	
	Manually	By Sensor
1	5	5
2	5	5
3	5	5

Interpretation of Data:

The prototype and manual testing results were equal each time the test was performed. These results mean that there was a 0% error which is well below the 10% error margin outlined in the requirement table. Based on this testing, there is no need for this device to be redesigned or revised regarding the chosen requirement. If the course allowed, aspects of this design could now be prototyped, and a higher fidelity sensor could be made. The testing was performed in a small room with flat floors. These conditions are not ideal as they do not mimic the rough terrain and longer distances that an average wheelchair user would encounter daily. These conditions could cause the results to have increased error. The prototype was also not able to be secured in the correct location. In the concept sketches, the sensor was attached just behind the wheel that would track every time a specific point on the wheel passed by it. This configuration could not be accomplished with the materials on hand during prototype testing, so the sensor was attached to the armrest just in front of the wheel. If testing were to be performed again, the team decided it would be better to perform it outdoors and for a longer distance so that these conditions could be analysed when considering error margin.

Conclusion

This project set out to address the situation of concern, and by doing so, help wheelchair users exercise. To effectively formulate a solution to the outlined problem, research was conducted in order to create requirements and constraints which assisted in identifying the most important project objectives. Following that, personas for potential future users were developed to provide a more comprehensive understanding of the problem space. An additional three ethical requirements were developed after iterating on the needs assessment to ensure the proposed solution was ethical in all regards. Using a QFD chart, the engineering requirements were compared to one another, to competitor products, and to user needs. The device's primary and secondary functions, as well as the unwanted functions, were developed, and the methods for achieving the functionality were documented. To begin the iterative design process, several design concepts were drawn, and the three that best addressed the situation impact statement were chosen and compared using a best of class chart. The best elements from the top designs were taken and applied to a final design concept. The final design featured a physical device mounted to the wheelchair to collect physical motion data as well as an interactive mobile phone application to present exercise data and aid in the tracking of holistic health aspects. Statics-based engineering analysis revealed that the device did not obstruct wheelchair movement, meeting the primary constraint “must not impede wheelchair movement”. A low-fidelity prototype was created utilizing Arduino components for the device's circuitry and a cardboard box as the structure. Multiple tests of the prototype concluded that the device provided accurate readings regarding wheel rotations. Plans were made to test a medium-fidelity prototype, with the new prototype to use more refined materials and wheelchair mounts, allowing for the device's ease of installation and adjustability to be tested in addition to a wider range of data collection.

The design concept satisfies all outlined requirements. It sends movement data to an accompanying mobile phone app, which receives the data and visually presents it to help motivate users to achieve their goals. Furthermore, the mobile application includes social features that use competition with friends to motivate users to exercise. The materials outlined in the design are affordable and allow for the design to be realistically manufactured. Testing of the prototype shows that the device can accurately track rotation data – the first step in tracking a wider array of information. That being said, further user testing with a higher fidelity design is required to study how the device truly impacts how much exercise self-propelled wheelchair users complete. This project has yielded a feasible design that meets the situation impact statement, and allows for further testing. Depending on the results of said testing, this design could be incredibly beneficial in motivating users to exercise more frequently. By addressing the situation impact statement, the work completed in this project is a successful first step in helping increase exercise amongst self-propelled wheelchair users.

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Appendix

Figure 4 : Free body diagram of the prototype, point A representing the point of contact and W representing the centre of mass.

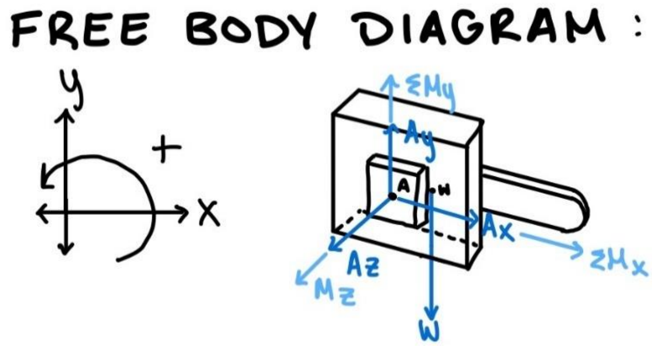

Figure 5 : Front and side view of prototype for engineering analysis, including dimensions.

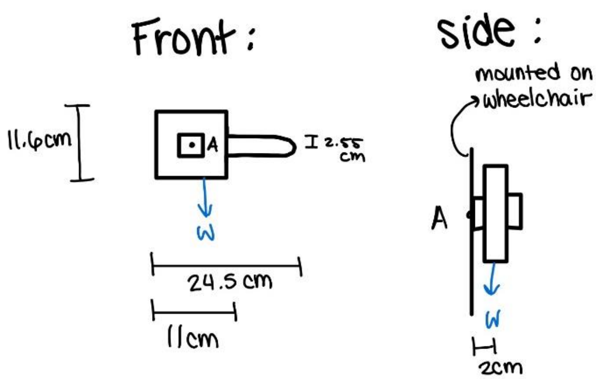

Figure 6: Accompanying calculations for the free body diagram

calculations:

x-direction: $R_x = \frac{24.5cm}{2} - \frac{11cm}{2}$

$= 12.25\,cm - 5.5cm$

$= 6.75cm$

y-direction: $R_y = 0cm$

z-direction: $R_z = -2cm$

2D equilibrium:

$\Sigma F_x = 0$

$A_x = 0$

$\Sigma F_y = 0$

$A_y - 450g = 0$

$A_y = 450g$

$A_y = 0.45(9.81)N$

$A_y = -4.4145N$

$\Sigma F_z = 0$

$A_z = 0$

$\Sigma M = M_x\hat{\imath} + M_y\hat{\jmath} + M_z\hat{k} = 0$

$$\Sigma M_A = \begin{vmatrix} \hat{\imath} & \hat{\jmath} & \hat{k} \\ 6.75 & 5.8 & -2 \\ 0 & -4.4145 & 0 \end{vmatrix} = 0$$

$0 = -(-4.4145\,N)(-2cm)\,\hat{\imath} - 6.75cm(4.4145N)\,\hat{k}$

$0 = -(-4.4145\,N)(-0.02m)\,\hat{\imath} - 0.0675m\,(4.4145N)\,\hat{k}$

$0 = -0.0829Nm\,\hat{\imath} - 0.29798Nm\,\hat{k} = \Sigma M_A$

$\Sigma M_A = -8.29 \times 10^{-2} Nm\,\hat{\imath} + 2.98 \times 10^{-1} Nm\,\hat{k}$

$\therefore$ The sensor exerts -8.29×10^{-2} NM in the i direction and 2.98×10^{-1} Nm in the $\hat{k}$ direction.