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Smart Walker - BME 301
Preliminary Report
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BME 301: Biomedical Engineering Design

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Abstract

Patients recovering from Traumatic Brain Injury(TBI) often lose their ability to walk and must undergo Physical therapy to rehabilitate their legs and neural pathways involved in walking. This is a two-week-long process that involves a number of therapies. As they undergo therapy, they have to perform a 10m walk test, in which they walk 10 meters, and the practitioner times them to see how they progress day by day. The biggest challenge when tracking progression is the fact that there is no commercially available method of testing the weight that the patient puts on the walker, as well as human error being involved in manual time trials. This is problematic for the client because Insurance providers need precise metrics in order to cover costs, and patients have no way to track their own progress as they undergo therapy. The system will include load cells to measure the weight put on the walker, and sensors that track movement speed, and distance traveled. This system will connect to a mobile device interface that will allow storage and display of the data. This will allow the client to accurately monitor progress, giving insurance providers and clients concrete data to show progression. Testing will include a series of trials that will measure: the accuracy of the distance and speed sensors across a known distance, and a series of known weights on the walker, to determine the accuracy and sensitivity of the load cells. By designing a system that can track distance, speed and weight accurately, we hope to change the future of stroke and TBI recovery for the better.

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1. Introduction and Background

1.1. Overview

The Smart Walker is a modular rehabilitation monitoring system that attaches to existing clinical walkers to objectively measure patient mobility metrics during neurorehabilitation. This system incorporates force sensors, a distance and speed tracking sensor, and a real-time display interface to quantify weight-bearing, walking speed, and distance traveled. This is particularly important for patients with traumatic brain injury (TBI), who often experience hemiparesis, impaired balance, and asymmetrical weight-bearing due to damage to motor control pathways.

In contrast to traditional walkers that offer only mechanical support, the Smart Walker serves as a clinical assessment tool. It delivers quantitative and repeatable data to document patient progress, inform discharge decisions, and facilitate insurance reimbursement. The system remains compact, removable, and fully compatible with standard aluminum clinical walkers, while preserving structural integrity and patient safety.

1.2. Context and Motivation

Patients recovering from traumatic brain injury (TBI), stroke, and other neurological impairments frequently rely on walkers during rehabilitation. Clinicians commonly use standardized tests, such as the 10-Meter Walk Test, to evaluate progress. However, current assessment methods are predominantly manual and subjective. Therapists are required to estimate weight distribution visually, manually time walking trials, and approximate distance traveled.

The absence of objective data introduces several challenges: limited availability of quantifiable evidence of patient improvement, difficulty in demonstrating medical necessity to insurance providers, and reduced capacity to monitor subtle changes in gait stability and patient motivation due to lack of measurable feedback. The Smart Walker addresses this gap by transforming a passive mobility aid into an active rehabilitation measurement tool. By collecting real-time force and distance data, the device enables clinicians to make data-driven decisions and increase transparency in patient progress documentation.

Existing smart mobility devices are frequently expensive, complex, or primarily designed for independent living and fall detection rather than clinical rehabilitation tracking. Consequently, there is a significant opportunity for a compact, affordable, clinic-focused monitoring attachment system.

1.3. Problem Statement

Currently, rehabilitation clinicians do all tests involving patient progress by hand, timing how long it takes a patient to walk a certain distance. Clinicians lack a system that objectively measures and documents weight-bearing, walking speed, and distance during walker-assisted therapy without compromising walker stability, safety, or usability.

Standard progression metrics do not measure applied force or gait metrics, requiring clinicians to rely on manual observation, which lacks precision and repeatability. Additionally, insurance providers increasingly require objective metrics to justify continued rehabilitation services. Lastly, existing smart mobility devices are expensive, bulky, or intended for long-term monitoring rather than short clinical trials.

Accordingly, the Smart Walker must: measure forces ranging from 0 to 100 kg, measure speeds ranging from 0 to 9.65 km/h, track walking distance accurately to within 10% or less, remain detachable, lightweight, and compatible with standard walkers.

The engineering challenge is to integrate sensing technology into a walker without altering its mechanical performance, increasing fall risk, or exceeding cost and size constraints.

1.4. Competing Designs

Most commercial mobility aids prioritize walking assistance and user safety over quantitative gait measurement or rehabilitation tracking. The Bure Rise & Go Walker (~$7,746) [1], as seen in figure 1 is designed for powered standing and transfer assistance, incorporating an electrically operated remote control and braking casters to enhance caregiver-managed safety. However, it lacks the capability to measure gait or pressure metrics. Likewise, the U-Step Neuro Walker (~$124 [2]), as seen in figure 2 focuses on balance and stability through a mechanical hand brake system but does not include integrated electronics or data monitoring features.

The Rollz Motion Rhythm Neuro Rollator (~$1,999 [3]) most closely aligns with the concept of a smart walker among current products. Intended for individuals with Parkinson's disease and other neurological gait disorders, it integrates three cueing systems: laser, audio, and vibration, to encourage steady walking. These cues can be customized via a Bluetooth-connected mobile app, and the device folds for easy transport. Although it enhances gait through external cueing, it does not offer detailed quantitative gait analysis or rehabilitation progress monitoring. An image of this walker can be seen in figure 3.

Research prototypes incorporating FlexiForce™ sensors illustrate ongoing efforts to integrate force sensing into walker designs. These systems translate applied force through a microcontroller and transmit data via Bluetooth for further processing. Frequently, they use inertial measurement units (IMUs) to estimate gait metrics rather than directly measuring walking speed [4]. The Camino smart walker (~$2,999 [5}) includes advanced assistive features such as auto-boost, auto-brake, lighting, and application connectivity, but it primarily serves as an intelligent mobility aid rather than a rehabilitation monitoring device. Overall, the current market demonstrates a gap between high-cost assistive automation and low-cost mechanical walkers, with limited options that integrate sensing, connectivity, and quantitative gait monitoring within a single device. An image of the Camino smart walker can be seen in figure 3.

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Figure 1*: Bure Rise and Go Walker [1]*

Figure 2*: U-Step Neuro Walker [2]*

Figure 3*: Rollz Motion Rhythm Neuro Rollator [3]*

Figure 4*: Camino Smart Walker [5]*

2. Preliminary Designs

2.1. Hardware Flow

2.1.a. Sensor Research and Designs

Concept A: The first concept for the distance sensors focuses on using ultrawideband (UWB) sensors with a Wi-GIM Network. These sensors are relatively compact in size and an image of the

UWB sensors can be found below in figure 5. A UWB sensor works by emitting billions of nanosecond radio pulses across a wide spectrum of frequencies, up to 500MHz, and calculating distance via Time of Flight, based on the speed of light. By measuring the round-trip time of these pulses between devices, UWB provides highly precise, centimeter-level location, ranging, and spatial awareness [6]. In the application of this project, there would be one sensor on the walker itself and one sensor on the wall, which the user will walk to, to receive the signals emitted from the sensor on the wall. The UWB sensors will work with a Wi-GIM network, which has commonly been used to measure ground instability in landslide-prone areas [7], but when applied to the applications of this project, can detect the stability with which the patient is walking, and add another metric of rehabilitation progress for the patient.

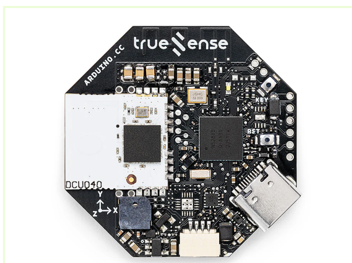


Figure 5*: Ultra-wide band sensors with dimensions of 38 x 38 x100 mm[8]*

Concept B: The second concept utilises a gyroscope with an accelerometer. A gyroscope is a sensor that measures and/or maintains orientation and angular velocity, and is best used in inertial systems to supplement other sensors that can exhibit location errors [9]. An accelerometer is an electromechanical sensor that measures acceleration by detecting forces acting on a proof mass [10]. This type of sensor would be beneficial in the applications of this project as it provides another metric of a patient’s rehabilitation progress, which would be how fast a patient would be walking. An image of this sensor system can be seen below in figure 6.

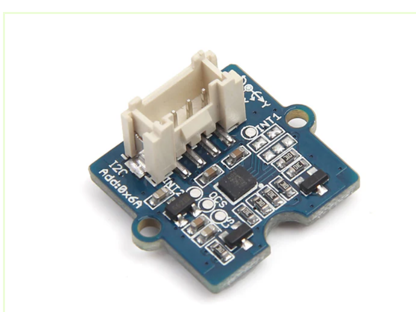
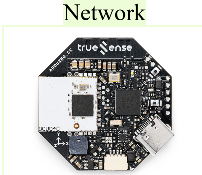


Figure 6*: Accelerometer and Gyroscope sensor with dimensions of 140 x85 x10.3mm [11]*

Concept C: The third concept focuses on using mmWave radar. This type of sensor measures distance with high precision by analysing frequency-modulated continuous waves. This sensor measures distance by calculating the time of flight of radio waves reflected from the other object the sensor is on, in this case, the wall. The typical maximum range for this type of sensor is 8-10m [12]. This sensor also has the capability to measure the velocity at which the patient is travelling, which is a good metric to consider in terms of a patient's rehabilitation process. An image of this sensor can be seen below in figure 7.

***Figure** 7: mmWave Radar Sensor with dimensions of 24 x28mm[13]*

2.1.b. Design Matrix for Sensors

Criteria (weight)	Concept A: UWB + Wi-GIM Network 	Concept B: Gyroscope + Accelerometer 	Concept C: mmWave Radar 

Accuracy (30)	5	30	3	18	4	24
Consistency (25)	4	20	3	15	5	25
Occlusion Sensing (20)	4	16	3	12	5	20
Size (10)	3	6	5	10	4	8
Power Consumption (10)	2	4	5	10	2	4
Cost (5)	1	1	5	5	3	3
Total (100)	**77**		**70**		**84**	

Table 1: *Design matrix outlining the 6 criteria for 3 different designs for the sensors and their respective scores. The green-highlighted categories indicate the highest scores of the three designs in the specific category. Scores are out of 10 points; displayed as Score | Weighted Score.*

Accuracy: Accuracy was weighted at 30/100 and identified as the critical focus for this project, as this device will be used in a medical rehabilitation setting, so it is extremely important that the patient and their doctor know the true progress of their rehab. Accuracy considers the detailed reading of the distance travelled [14] by the patient, serving as a metric of how far they can walk without needing to take a break, as well as the stability with which the patient is walking with, which is another metric for rehabilitation progress. For this criteria, the ultrawide-band sensors with the Wi-GIM network scored the highest as the readings obtained as UWB sensors have high accuracy in measuring distances, coming within a few centimeters [15], and in cooperation with the Wi-GIM network, would add more ways to measure a patient's progress. It should be noted, however, that UWB sensors work best when there is minimal occlusion; as occlusion increases, distance readings deviate further from the true value [16]. Concept C was a close second,d but certain atmospheric variables, such as high O_2 levels and moisture affects the reading values [17]. Additionally, it works best in small ranges, and increasing the maximum range can cause environmental noise, which decreases precision [17]. If the patient wants to increase the distance they walk, this measurement method would not be accurate for tracking their progress. Concept B scores the lowest as the accelerometer is best suited in situations of linear acceleration, and gyroscopes are best suited for angular velocity [18], which are not the scenarios in which it would be used for this project, despite providing accurate readings.

Consistency - Consistency was weighted at 25/100, being the second most important criterion for the sensors, and is a measurement of how close the values obtained by the sensors are to one another. Concept C scored the highest in this criterion as mmWave radars have extremely high precision of as low as below a mm, and due to the frequency range in which it operates in, the sensor uses short wavelengths to detect minute movement and changes in distances [19]. The frequency range it operates in is 60GHz-81GHz, and this higher bandwidth allows for higher range resolution for recorded values, and in human tracking scenarios, which is exactly the scenario it would be used for this project, mmWave Radar sensors can have up to 98% precision [20]. Concept A scored the second highest in this criterion, while the accuracy of the readings obtained from UWB Sensors in a Wi-GIM network is extremely high, it does exhibit high precision as well, just not precision as high as a mmWave Radar Sensor. The typical precision of a UWB sensor is within a range of a couple centimeters, and can even go up to 10cm [21]. Concept B scored the lowest for this criterion, as the precision is based on different axes [22], and provides high precision when working in low measurement ranges, but in the situation where a patient would want to increase their distance range, this would lead to less precise values obtained from the accelerometer and gyroscope sensors.

Occlusion Sensing - Occlusion sensing is weighted at 20 out of 100 because reliable distance and speed tracking in a real-world clinic scene requires sensors to continuously measure accurate parameters, even when obstacles such as therapists' assistance, furniture, or other people walking by. Concept C, the mmWave radar, scored highest here because mmWave radar signals operate in 30-300 GHz band and have documented capability to penetrate soft materials or diffract around partial obstructions[23][24]. Concept A's UWB + Wi-GIM network performs moderately with a ⅘ score. With a similar ability for multipath robustness and occlusion tolerance to mmWave radar, its accuracy, however, degrades as obstruction increases, leading to more error in time-of-flight measurements [25]. Concept B's combination of accelerometer and gyroscope scored lowest with a ⅗. This combination does work very well in the "people walking by" scenario since sensors are not affected by line-of-sight at all, but it lacks an external reference for distance, thus other environmental obstructions like patient irregular body movement or walker feet slipping could produce unrecoverable occlusion in distance and speed tracking[26].

Size - The physical footprint of the sensing hardware was the primary factor influencing the size scores, with board dimensions having a greater impact than weight. The UWB-based concept uses modules from Digi-Key [27] that are generally larger than those of alternative sensor options. Development-ready UWB boards, such as the UWB Click or similar transceiver modules, are breakout boards intended for mounting on a carrier board and typically measure 40-60 mm across when assembled. This size is due to the inclusion of connectors and support circuitry, rather than just the transceiver chip. Although the core radio chip is small, the overall integration form factor remains bulky. Consequently, UWB received the lowest score for size, despite reasonable power and weight performance. In contrast, the inertial sensor used in Concept B, such as the Adafruit TDK InvenSense ICM-20948 [28] or the lower-cost TDK InvenSense ICM-40609-D [29], is a compact chip-level module measuring approximately 3 × 3 mm. Even when mounted on small breakout boards, the size rarely exceeds 10 × 10 mm. This compactness facilitates integration into constrained designs, resulting in a mid-range score for Gyro+Accelerometer in this category. The mmWave option achieved the highest score for size because radar sensors such as the Acconeer AB XM126 A121 IOT Radar Sensor [30] are manufactured as small integrated modules, typically measuring 12-15 mm per side. These modules incorporate both the RF front end and processing components on a single compact board. This minimal footprint enables efficient integration of motion and ranging sensing, contributing to the top ranking in size. Although individual weights differ, differences in PCB-level form factors were the primary determinant in the ranking.

Power consumption - This criterion captures the amount of power the sensors use while in use and was weighted at 10/100, as distance sensors run on battery power, which is vital for tracking real-time distance data. However, it wasn't rated higher because most of these batteries are expected to last 1-2 years without replacement or recharging [31]. Between the three sensors, concept B, Gyropscope, and accelerometer won with a score of 10/10 as it uses a very low power scale of between 3-10mW, which is why it is often used in applications of continuous monitoring [32]. Both concepts A and C, UWB and mmWave Radar, scored the same with a 4/10, because they seem to use an average of 50-200mW, with some mmWave Radar options going from 1-5W depending on range/resolution [33]. Both sensors may require more frequent monitoring, which could be inconvenient for the therapist or user.

Cost - While cost is not a major issue for us, we want to be mindful of the price of each sensor component to ensure cost-effectiveness, so the client can make more attachments to his other patients. That is why this criterion was weighted 5/100. From the three sensors, concept A, the gyroscope and accelerometer were weighed as the cheapest option, given a 5/5, as the standard GY-521 MPU module can cost from $1 to 3$ and other higher quality modules like MPU-6050 can cost from $10 to $20 [34]. The mmWave radar was rated a 3/5 as a consumer-grade sensor, typically costing $20 to $60 [25]. Lastly, the UWP was weighted the lowest at 1/5 as basic modules like DW1000 can cost from $30 to $90 upwards [36]. The more cost-effective the sensor, the more versions we can test, giving us room to pick the most accurate one.

2.2. *End Cap*

2.2.a. *End Cap Research and Designs*

Concept A: The integrated design includes a 3D-printed dish that supports the load cell and load cell system above the walker's existing end cap. This design includes three different components that fit into one another, the base, the middle section which is what houses the load cell and the load cell system, and the top section which protects the load cell from external damage and clips the endcap onto the walker. This end-cap design allows for a greater lifespan of the end-cap, allowing for the end caps to be used for a greater period of time without having to be replaced. An image of this end cap design can be seen below in figure 8.

Figure 8*: CAD design of the integrated end-cap design. The design included three separate sections with the base having dimensions of (30mm), the middle section having dimensions of (24mm), and the top section having dimensions of (25.4mm x 30mm)*

Concept B: The custom endcap mimics the design of common end caps already used in the market by providing a space with the load cell embedded in the shape and a rubber coating at the bottom to provide a constant force across the surface area. The end cap design is specific to the load cells used and the type of walker, so the design would need to be customised for each patient. An image of this endcap design can be seen in figure 9 below.

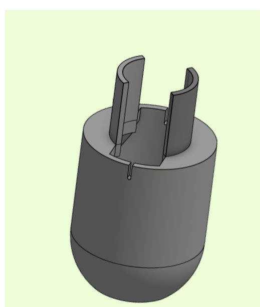


Figure 9*: CAD design of custom endcap design, with dimensions of the bottom endcap section being 70 x 90mm, and the top section which will clip onto the walker leg being 25.4 x 30mm.*

Concept C: The sled end cap shares the same features as the custom end cap, with the load cell embedded within the end cap and the rubber coating, but the rubber coating extends onto a sled-shaped piece at the back to provide extra support to the walker. This design does have a thinner rubber coating on the bottom so may be prone to wearing out more quickly. An image of this design can be seen below in figure 10.

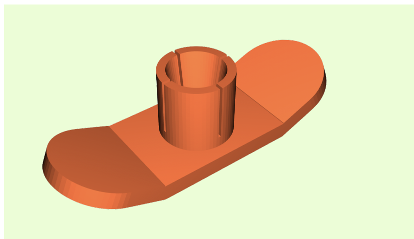
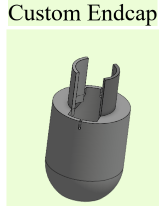
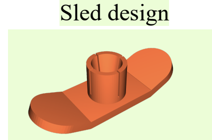


Figure 10*: CAD design of the sled endcap design. The dimensions of this design are 120 x 100mm for the bottom rubber coating, and 25.3 x 30mm for the top section which clips into the walker leg.*

2.2.b. End Cap Design Matrix

Criteria (weight)	Concept A: Integrated Endcap 		Concept B: Custom Endcap 		Concept C: Sled design 	
Durability (25)	*5*	**25**	*4*	**20**	*3*	**15**
Cost (25)	*4*	**20**	*3*	**15**	*2*	**10**
Reproducibility	*5*	**25**	*4*	**20**	*4*	**20**

(25)						
Ease-of-Use (15)	*3*	**9**	*5*	**15**	*4*	**12**
Safety (10)	*4*	**8**	*5*	**10**	*4*	**8**
Total (100)	**87**		**80**		**65**	

Table 2: Design matrix *outlining the end cap designs and their respective scores. The green-highlighted categories indicate the highest scores of the three designs in the specific category. Scores are out of 10 points; displayed as Score | Weighted Score.*

Durability - Concept A (Integrated design) ranked highest in durability and reproducibility. Its unified structure reduces joints and potential failure points, resulting in a longer service life and fewer breakdowns, which are key measures of product durability in engineering quality standards (durability reflects a product's lifespan and resistance to wear) [37]. The design also scored highest for reproducibility because integrated structures are typically easier and more consistent to manufacture. This aligns with design-for-manufacturability principles that emphasize minimizing part count to reduce variation between units (manufacturability improves consistency and lowers defect rates) [38]. Its strong cost score reflects these advantages, as fewer components and simplified assembly usually lower production expenses, even if initial tooling is more involved.

Cost - Concept B (Custom Endcap) received the highest score for ease-of-use, indicating that its custom features or ergonomic design likely enhance user intuitiveness and facilitate installation and maintenance, which are central objectives in product design (ease-of-use minimizes user effort and errors)[39]. In contrast, its moderate durability and cost scores likely result from the added complexity of custom features, which can introduce additional fabrication steps and potential points of wear. Concept C (Sled design) excelled in safety, implying that its larger geometry or protective components effectively reduce operational risks, aligning with product design principles that emphasize user protection and hazard mitigation (safety features reduce accident rates). Nevertheless, Concept C ranked lowest overall because sled-style mechanisms typically require more material and more complex assembly, leading to higher costs and reduced reproducibility compared with the other concepts. Collectively, these rankings illustrate the inherent trade-offs among robustness, manufacturability, usability, and safety that shape engineering decision-making.

Reproducibility - This criterion is weighted at 25/100 and evaluates how easy it is to make bulk amounts of the design. The Smart Walker is intended for bulk production across multiple clinics, which requires the end cap design to maintain identical performance across production batches. Concept A, the integrated endcap, scored a full mark because it just utilizes the existing cap on the walker and fits the load cell into the empty spaces. Concept B, the custom endcap, scored ⅘ since CAD is a new part from scratch, increasing the potential for variation. Accurate 3D printing is only possible during the prototyping stage; mass production of a fully custom component often requires specialized tooling and tighter tolerances, which can increase production inconsistencies. Concept C, the sled design, scored the same as concept B because it shares the same drawback as a custom component. An additional mounting structure might be needed, introducing more assembly steps and potential human error, which reduces repeatability across units.

Ease-of-Use - This criterion was weighted at 15/100 and is defined as how easy it is for the user to put the walker cap on and remove it for replacement. Although each design will be tailored to the walker, there may be one or two features that make it difficult for the user to adapt to. Concept B, the custom end cap, won this category with a full score of 15/15. As mentioned earlier, it will consist of a covering on the end of the walker leg. There are no additional features to attach to the leg, making the placement process straightforward. Concept C, sled design was weighted next with a score of 12, and this was ranked lower than concept B because this design includes an extra sled feature at the back of the end cap for walker stability, but if the end cap is removed while only grabbing onto the sled piece, there poses a risk of the end cap breaking and constant usage of the walker can do the same. Lastly, concept A, the integrated end cap, was ranked as the lowest because

Safety - This criterion was weighted at 10/100 as the walker system will be used by patients who already have difficulty walking, and a lack of stability could affect their confidence and the process of improvement. Concept B, the custom end cap, received a score of 10/10 because the original rubber end cap design provides high slip resistance due to its increased friction with the ground, improving stability. Both Concept A and C received the same score of 8/10. Concept C, the sled design, is designed to glide more smoothly, but lower friction increases the risk of slipping, which also makes the design less compatible with wet flooring or outdoor concrete. For concept A, the safety risk stems from the design's complexity, and adding the sensor's placement could add unnecessary weight to the walker and interfere with the patient’s movement, further increasing the safety risk.

3. Final Design

The final Smart Walker design involves using integrated end caps which will house the load cells, which will measure how much force is being applied to the walker, serving as a metric on how much support the patient needs to walk. Additionally, in order to track the distance the patient has travelled, mmWave Radar sensors will be utilised, and the sensors will be placed in the electrical housing component that is attached to the walker. The mmWave radars require a receiving sensor, which will be anchored onto the wall the patient will walk to, in order to get accurate data measurements. Figure 11 below demonstrates the electrical circuit that will be created and housed in the electrical housing unit, in order to make the sensors and load cells functional.

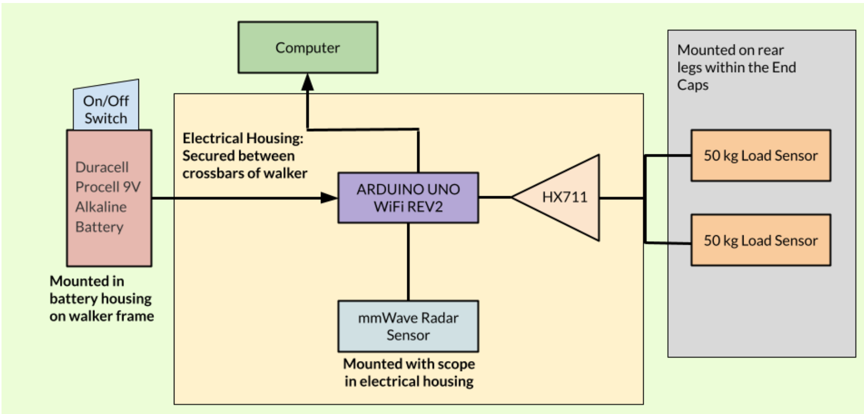


Figure 11: *Circuit Diagram Flow for Electrical Attachments*

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4. Methods

The Smart Walker system was constructed by integrating two 50 kg load cells into custom 3D-printed end caps attached to the walker's rear legs. The end caps will be modeled in CAD to securely house the load cells while maintaining structural alignment with the walker frame. They will be fabricated using 3D printing and mechanically fastened to ensure stability. Each load cell was connected to an HX711 load cell amplifier, which interfaced with an Arduino Uno WiFi Rev2 microcontroller located within a central electrical enclosure secured between the walker crossbars. The enclosure is designed to protect internal circuitry while maintaining accessibility for maintenance and future sensor upgrades. The system was powered by a 9V battery connected through an inline power switch.

The load cells were calibrated with known static weights to establish a force-to-voltage conversion factor. Multiple trials were conducted to verify the linearity and repeatability of the measurements. The LiDAR module was installed at the front of the electrical housing and aligned toward a fixed wall target. The team plans to replace this with mmWave Radar, but the concept remains the same. Distance measurements were validated against tape-measured values to assess baseline accuracy. All sensor data was transmitted from the Arduino to a computer via serial communication for real-time monitoring and logging. Custom software was developed to simultaneously sample force and distance data, enabling synchronized analysis of walker loading and displacement during testing trials.

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5. Testing and Results

5.1. mmWave radar occlusion sensing testing

This test is intended to validate that mmWave radar-based sensing can still detect or track distance and speed under realistic occlusion conditions common in rehabilitation walking, including legs, hands, furniture, and people walking by. To accomplish this, the mmWave radar module will be mounted in the front of the electronic enclosure, with the walker placed in an open hallway. Testing conditions will include a no-occlusion baseline, partial occlusion with hands intermittently blocking the radar, and full occlusion with people stepping between the radar and the wall. Each scenario will perform 3 repeated trials and compare the output to the tap-measured path length. Metrics include track continuity, recovery time after occlusion, distance error vs ground truth, false positive rate, and dropout rate. [40]

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5.2. Load cell measurement testing

The accuracy of the load cells will be evaluated by comparing their recorded values to those obtained from a pressure scale with a known level of accuracy. To accomplish this, incremental weights (up to a maximum of 100 kg) will be applied to both the walker and the reference scale. The measurements from each device will then be compared to assess the consistency of our data between these two measurement systems. Multiple trials will be conducted to collect more accurate data. Statistical analysis will be performed on the outcomes, including the percent error and RMSE across calibration loads, standard deviation across repeated trials at each load, and reading drift over time at constant load.

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5.3. Wireless connectivity testing

This test is intended to validate that the new wireless transmission pattern of combined WiFi and Bluetooth supports continuous and reliable data logging in realistic environments. The equipment will be tested in different environments: quiet home WiFi as the baseline, campus/clinic WiFi, and a Bluetooth-only fallback scenario. For the baseline throughput test, the transmission will stream for 10 minutes at the target packet rate, and log packets, latency, and dropouts. Then the smart walker will be tested while walking a fixed route, including transitions gradually away from the router and behind the walls. The last test will be a failover test, which forces WiFi loss by turning off the AP and measuring the time to switch to Bluetooth and whether data continuity is preserved. Metrics to be analyzed will include packet delivery ratio, dropout count and duration, latency, and data loss during handoff.

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6. Discussion

Based on the testing results, we determined the feasibility and effectiveness of using the smart walker device in clinical settings. It is important that load measurement, speed, and distance testing are accurate, as these are the key quantitative identifiers in the client requirements, and their accuracy will be used to confirm the reliability of our device. If any of these tests initially fall below the desired standard, modifications will be made to improve the system and ensure data consistency. The mmWave radar sensor must match the measured distance and produce speed values that match the manually calculated speeds based on the stopwatch. The closer the values are, the more likely the mmWave radar sensor is to be suitable for tracking patient movement during indoor walking trials. The mmWave radar sensor must also be accurate up to 150ft, as that is our goal this year, and must surpass the 120ft from last year's LiDAR sensor. The load cells must accurately record weight with two loads, regardless of the walker user's balance, and must withstand the actual weight. The load cell output must also be within ±2% of the actual weight. When the smart walker is in use, any recorded data needs to be in accordance with HIPAA, to protect patient identity and confidentiality [41].

Potential sources of error in the testing process, related to inaccurate measurement of distance and speed, can be due to signal blockouts caused by furniture or movement, resulting in spikes in readings [42]. In addition, mmWave radars are highly sensitive, which can lead to false positives. Potential sources of error in load measurement could include mechanical damage from overloading or uneven weight distribution. 3D-printed tolerances can also affect force transfer and electrical noise in the strain gauge amplifier.

7. Conclusion

This project aims to provide neurorehabilitation physical therapists and patients with an accurate and convenient way to track real-time measurements of patient performance, specifically of speed, pressure, and distance, without altering the safety or function of a standard walker. Through research and testing, it was determined that a modified version of Smart Walker 2.0 will include a sensor combination of load cells to measure pressure, an mmWave radar sensor to measure speed and distance. The mmWave radar sensor will improve occlusion sensing and reduce the impact of environmental factors compared to the previously used LiDAR sensor, making it an effective replacement. These components will provide accurate, reliable data while minimizing the walker's structural integrity, ensuring safety. An Arduino Uno WiFi Rev2 will be used to connect WiFi and Bluetooth data transmission and ensure that the system is compatible with a variety of platforms.

The team will successfully produce a proof-of-concept prototype that will meet all the client's requirements, with minimal error of ±2% compared to the manual and actual measurements, as shown in the load measurement testing and mmWave radar testing. Fabrication is straightforward and requires minimal unique parts apart from the sensor housing in the integrated end cap design, to ensure bulk production and ease of manufacturing. The cost for the entire system is also kept under the client's budget of $500.

Future work would involve soldering components permanently to a PCD board in order to avoid loose wires or mechanical contacts that can cause unstable readings or safety hazards. In addition, incorporating clinical trials and human subject testing with on-site patients can provide realistic feedback and help determine adjustments we can make, especially for ergonomics.

Commented [8]: Shreya

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10. Appendix

Appendix A: Product Design Specifications

Smart Walker - BME 301

Product Design Specifications

February 5, 2026

Updated: February 5, 2026

Section 302

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Function:

Patients with traumatic brain injury (TBI) frequently experience significant trauma followed by intensive rehabilitation aimed at restoring mobility and facilitating a return to daily activities. During rehabilitation, clinicians often face challenges in objectively measuring patient progress, limiting their ability to provide quantifiable feedback and to show insurance providers evidence of improvement, which complicates reimbursement for clinical services. The proposed smart walker accessories will objectively measure pressure applied, walking speed, and distance covered by patients during their daily evaluations. These data will be reported and displayed in real time to support clinicians in monitoring patient progress and enhancing patient motivation. Ultimately, the device is expected to streamline Medicare documentation requirements and provide objective indicators of patient readiness for discharge.

Client requirements:

- The device must measure pressure from 0-100kg, speed from 0-9.65 km/h, and track appropriate distances (limited constraint).
- The device must be suitable for both physical training sessions and everyday use.
- The device attachments must remain compatible with existing walkers without compromising their structural integrity.
- Each device attachment should be separable and usable both in tandem and individually.
- The device should be able to send real-time data to a mobile device and website, which will collect and display it.

- The device needs to be compact, user-friendly, accurate, and reliable within the project budget of approximately $500.
- The device must be easily sanitized for daily use, including domestic personal purposes.

Design requirements:

1. **Physical and Operational Characteristics**
   a. *Performance requirements:*
      i. The smart walker components should be easily detachable so that they can be connected to any walker.
      ii. The components, specifically the load sensor, should be able to withstand a load of 136kg, which is the standard load expected to be supported by a walker for patients undergoing rehabilitation with one-sided weakness, which is often the result of a stroke [1].
      iii. The electronic display should relay real-time information about the patient's walking pattern.
      iv. The electronic components and sensors should be able to measure weight-bearing, distance travelled, and speed travelled.
      v. All attachments to the walker should not impede its function or stability.
   b. *Safety:*
      i. The structural integrity and stability of the walker should not be compromised
      ii. The device must be able to withstand the weight of the patient.
      iii. All electrical components should contain ESD (electrostatic discharge) prevention.
      iv. All electrical components must comply with applicable ISO, IEC, and FDA requirements.
   c. *Accuracy and Reliability:*
      i. The walker must measure distances, speeds of 0-9.65km/h, and pressures of 0-100kg within 10% of the absolute values.
      ii. Metrics should be accurate over distances of at least 10m (standard 10-Meter Walk test)
   d. *Life in Service:*
      i. The walker accessories should withstand up to 50 trials per day over 10 years before requiring serious maintenance (electrical component replacement).
   e. *Shelf Life:*
      i. The walker is expected to last a standard shelf life of 3-5years as over time the rubber soles would wear out [2].

ii. The ultra-wideband sensor should last up to 7 years; it has a low frequency blink rate of 7Hz, but this low frequency would work for the application of this project [3].
iii. Load cells have a lifespan of 10 years. However, their lifespan is dependent on their fatigue life, specifically the number of cycles, so a load cell's lifespan is highly subject to its fatigue life [4].
iv. The HX711 amplifier board has a lifespan of between 5-10 years, although it is highly susceptible to damage due to environmental conditions, so it often doesn't reach its entire lifespan [5].

f. *Operating Environment:*
   i. Due to the number of electrical components associated with the attachments to the walker, the operating environment must be dry and indoors.
   ii. The walker will be used at the client's neurorehabilitation center, which will be at a temperature of 16-26 °C.
   iii. The walker will be used by multiple people, which will require sanitation between each use. The walker should be able to withstand continuous use of alcoholic disinfectants.

g. *Ergonomics:*
   i. The height of the walker should be adjustable to heights of 80-100 centimeters[6].
   ii. The width of the walker should be 60 centimeters. This will not be adjustable; however, the attachments designed can be switched between walkers if needed[same as citation in other bullet points].

h. *Size:*
   i. The attachments should be small enough to avoid interference with the patient's movement and easy to transition between walkers.
   ii. The components should not protrude from the existing walker by >10cm to ensure the walker still fits easily through doorways and can be stored effectively.

i. *Weight:*
   i. The attachments to the walker must be relatively light so they do not add significant weight to the preexisting walker.
   ii. Clinical walkers weigh between 4.5 and 9 kg; therefore, the combined weight of the smart walker attachments and the walker should not exceed this range [7].
   iii. Studies have found that the allowable attachment weight should be ≤5% of the user's body weight to ensure stability and prevent slower gait patterns [8].

j. *Materials:*

    i. Walker structures are most commonly made from aluminum tubing and can include rubber or composite materials for mechanisms/grips, which all provide a stable base for the attachments [9].
    ii. The end caps for load cells are 3D-printed from polylactic acid (PLA).
    iii. The attachments will include electronic hardware such as wires, load cells, an ultra-wideband (UWB) sensor, an HX711 amplifier board, and batteries.
  k. *Appearance:*
    i. Device attachments should be compact and integrated within the walker to maintain an unobtrusive appearance.
    ii. Real-time data should be displayed through an intuitive UI on both the website and the attachment display to make it easier for clinicians and users to read.
    iii. All electronic hardware should be concealed to extend the device's longevity and ensure patient safety.

2. **Production Characteristics**
  a. *Quantity:*
    i. There will be 1 final smart walker with three separate attachments: four pressure sensors with end caps to measure force, an ultra-wideband sensor to measure speed and distance, and a live reader display.
    ii. All attachments should be removable within 5-10 secs and be compatible with other walkers.
  b. *Target Product Cost:*
    i. The budget for the design is approximately $500. Load cells cost around $100 each, and UWB sensors cost range from $50 to $100 [10]. All other costs will be kept to a minimum.

3. **Miscellaneous**
  a. *Standards and Specifications:*
    i. The Smart Walker accessory device is for clinical rehabilitation environments and must comply with standards relevant to medical devices, assistive mobility, electrical safety, and patient data privacy.
    ii. Medical device standards: FDA 21 CFR Part 820 Quality System Regulation[11], with the newest amendment effective on February 2, 2026, incorporates ISO 13485:2016 Medical Device Quality Management Systems, serve as comprehensive guidelines and requirements for consistent medical design, development, production and servicing. ISO 14971:2019 Risk Management for Medical Devices [12] requires systematic identification, evaluation, and mitigation of risks of Smart Walker including device instability, inaccurate measurements, electrical hazards, and user misuse.

iii. Assistive mobility standards: ISO 11199-1:2021 Walking Frames [13] and ISO 11199-2:2021 Rollators [14], together specify strength, stability, fatigue resistance, and safety testing requirements of Smart Walker to ensure the attachments added to the walking frame do not compromise walker safety or performance.

iv. Electrical safety standards: IEC 60601-1-12:2014 Medical Electrical Equipment Safety [15] applies to electrical components, including pressure and distance sensors in the Smart Walker, used in clinical environments, covering protection against shock, overheating, and electrical hazards.

v. Patient data privacy requirements: The Smart Walker system might store, export, or transmit patient data including walking speed, distance, and applied pressure to floor, it may become part of a system handling Protected Health Information (PHI) and therefore must align with the Health Insurance Portability and Accountability Act (HIPAA) Privacy and Security Rules [16].

b. *Customer:*

i. Primary customers are rehabilitation clinicians and therapy facilities treating TBI and mobility-impaired patients, while secondary customers include hospital administrators and insurance providers.

ii. Customer needs including:

1. Objective and repeatable metrics for patient rehabilitation progress documentation
2. Real-time display of walking performance, in the format of both a display on the handles and a remote monitor at a distance.
3. Durable and low-maintenance hardware for daily clinical use
4. Intuitive interface usable by therapists and patients
5. Enclosed electronics to ensure safety
6. Potential capability with electronic medical recording systems

c. *Patient-related concerns:*

i. Patients using the device often have neurological impairments and mobility limitations caused by TBI, therefore the design should not impair the basic functions of a 2-wheeled walker by not increasing the walker's instability or the user's risk of falling. The device's weight and size must not significantly increase the walker's effort. Displays must be readable without forcing unsafe posture changes by the patients. Components must avoid sharp edges.

ii. In practical applications, Smart Walker must maintain fundamental durability and ease of use for patients. Materials used can tolerate routine cleaning and sanitization between patients. The system must operate reliably without requiring technical knowledge from patients.

d. *Competition:*

i. Existing products mainly focus on assisting patient movement instead of a clinical rehabilitation monitoring tool as Smart Walker. Therefore, those solutions fall into the following categories:

   1. Standard walkers and rollators: Conventional walkers only provide mobility assistance but do not record rehabilitation progress. Therapists need to rely on either subjective observation or manual timing and distance measurements during therapy sessions
   2. Smart mobility aids [17]: Some advanced walkers measure gait parameters or walking speed, like a competitive product by Camino Mobility [18]. But these systems are often designed for long-term monitoring and are extremely expensive ($2999 RSVP for Camino), complex, and impractical for routine clinical sessions.
   3. Fall prevention mobility devices: Certain smart walkers incorporate terrain sensing to support independent living of people with walking disabilities, but those designs are often in the format of home safety installations, wearable alert and monitoring systems, footwear, and mobility support furniture [19], which do not meet the Smart Walker customer needs.

ii. Thus, the purpose of Smart Walker differentiates itself from those competitive designs by serving as a clinical monitoring and documentation tool rather than a mobility aid. It provides objective metrics such as pressure support, walking speed, and distance to quantify rehabilitation progress.

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Appendix B: Expense Spreadsheet

Item	Description	Manufacturer	Mft Pt#	QTY	Cost Each	Total	Link
Walker	2-wheel walker, **gifted** by client	Performance Health Supply, Inc.	081561703	1	$136.73	$0	Link
Arduino Uno Rev 4	Arduino with wifi abilities for our code and electronics.	Arduino	Sku: ABX00087	1	$29.21	$29.21	Link
HX711 Amplifier	HX711 Load Cell Amplifier	SparkFun	SKU: SEN-13879	1	$11.50	$11.50	Link
Battery Housing	9v Battery Holder with ON/Off Switch for Arduino	Gikfun	EK2107	1	$19.28	$19.28	Link
					Total	$59.99	