DEPARTMENT OF
Biomedical Engineering
UNIVERSITY OF WISCONSIN–MADISON

Smart Walker - BME 301

Preliminary Report

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BME 301: Biomedical Engineering Design

Members:

Nicolas Mandalado (Leader)

Shreya Venkatesh (Communicator)

Navya Jain (BPAG&BWIG)

Xicheng Yang (BSAC)

Client:

Daniel Kutschera

Advisor:

Dr. Justin Williams, UW-Madison, Department of Biomedical Engineering

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.

Table of Contents:

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 a 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.

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.

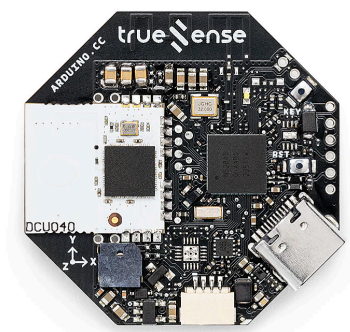


Figure 5: Ultra-wide band sensors with dimensions of 38 x 38 x100 mm[8]

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.

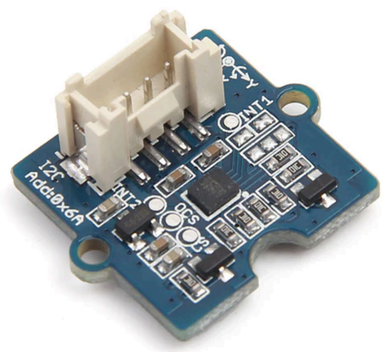


Figure 6: Accelerometer and Gyroscope sensor with dimensions of 140 x85 x10.3mm [11]

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.

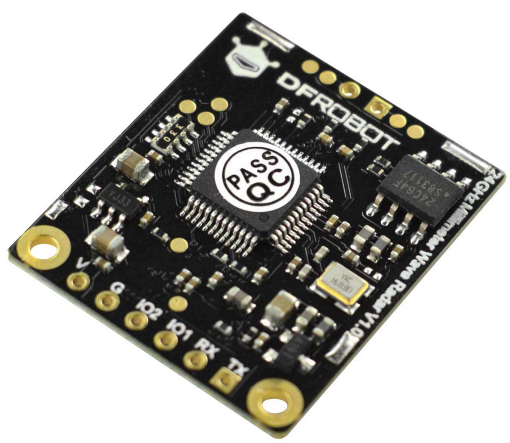


Figure 7: mmWave Radar Sensor with dimensions of 24 x28mm[13]

2.1.b. Design Matrix for Sensors

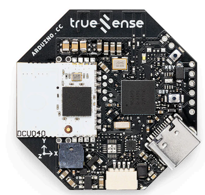
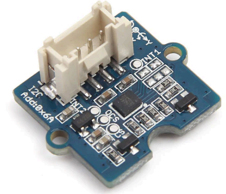
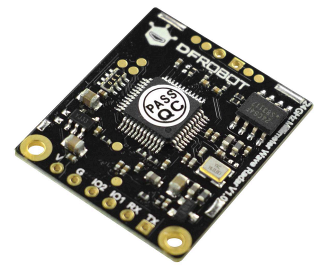
Criteria (weight)	Concept A: UWB + Wi-GIM Network 		Concept B: Gyroscope + Accelerometer 		Concept C: mmWave Radar 	
Accuracy (30)	5	30	3	18	4	24
Consistency (25)	4	20	3	15	5	25
Occlusion Sensing (20)	4	16	3	12	5	20
Size (10)	3	6	5	10	4	8
Power Consumption (10)	2	4	5	10	2	4
Cost (5)	1	1	5	5	3	3
Total (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.

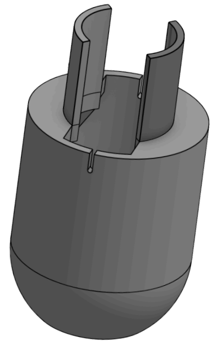


Figure 9: CAD design of custom endcap design, with dimensions of the bottom endcap section being 70 x 90mm, and the top section which will clip onto the walker leg being 25.4 x 30mm.

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.

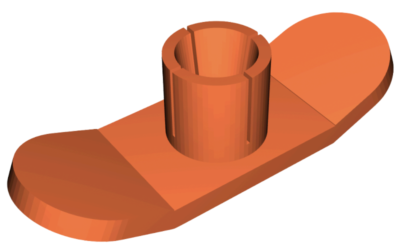


Figure 10: CAD design of the sled endcap design. The dimensions of this design are 120 x 100mm for the bottom rubber coating, and 25.3 x 30mm for the top section which clips into the walker leg.

2.2.b. End Cap Design Matrix

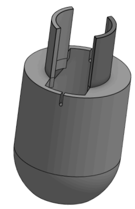
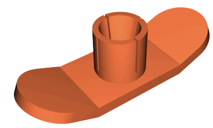
Criteria (weight)	Concept A: Integrated Endcap 		Concept B: Custom Endcap 		Concept C: Sled design 	
Durability (25)	*5*	**25**	*4*	**20**	*3*	**15**
Cost (25)	*4*	**20**	*3*	**15**	*2*	**10**
Reproducibility (25)	*5*	**25**	*4*	**20**	*4*	**20**
Ease-of-Use (15)	*3*	**9**	*5*	**15**	*4*	**12**
Safety (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 commercially available end caps, with a load cell housing encapsulating all required load cell hardware, 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 have a cutout from the electrical housing box to ensure reliable 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.

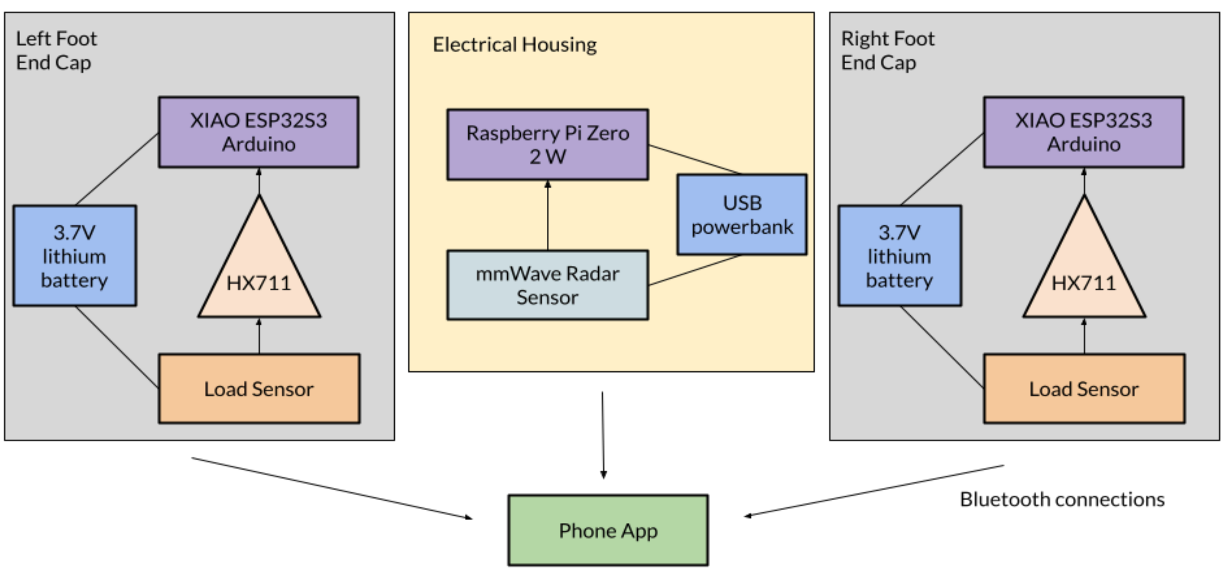


Figure 11: Circuit Diagram Flow for Electrical Attachments

3.1. Load detection

Load sensing is implemented using two 100 kg single point load cells from ATO, with model ATO-LCBU-DYHW-113. Each load cell is embedded within a circular housing attached to the rear legs of the walker. Each circular housing contains and soldering connected a load cell, an HX711 load cell amplifier from Sparkfun, a Seeed Studio XIAO ESP32S3 microcontroller, a 3.7V 2200 mAh lithium ion cylindrical battery, and a three-pin switch, as shown in Figure 12. The purpose of this system is to quantify how much the body weight the patient transfers onto the walker.

Each load cell produces a small differential voltage signal when force is applied. Because this raw signal is too small to be read directly by the microcontroller, the HX711 module is used for signal amplification and analog-to-digital conversion. The HX711 is connected to the ESP32S3 using two digital pins: DOUT on pin GPIO3 and SCK on pin GPIO2. Calibration is performed using known weights to establish a linear relationship and the calibration factor used in current code is 90,367.5. This factor converts the raw HX711 output into accurate pound readings.

Since the XIAO ESP32S3 microcontroller features a power management chip, the battery of this subsystem could be charged by connecting the USB-C port on the microcontroller. A red LED on board indicates the charging status: blinking indicates charging, constantly on indicates fully charged, and off indicates battery not connected and the system is powered by USB port.

Each foot module communicates with the mobile application using Bluetooth Low Energy (BLE). In current implementation, the two ESP32s are configured as BLE peripheral devices named SW-LeftFoot and SW-RightFoot. All peripherals share common UUIDs and are recognized by different devices names:

SERVICE_UUID "A7E8F0B1-3C54-4D92-9F3E-0A1B2C3D4E5F"
CHARACTERISTIC_UUID "B8F9E1C2-4D65-5EA3-A04F-1B2C3D4E5F60"

The system sends load data every 200ms, corresponding to an update rate of 5 Hz. This rate is sufficient for displaying real time changes. All source codes are included in Appendix E.

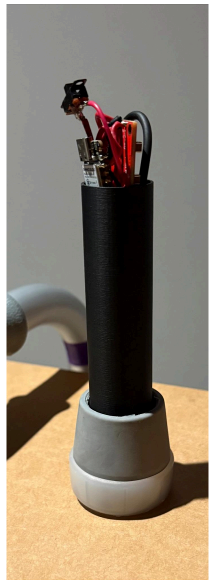


Figure 12: Load cell circular housing and components

3.2. Position detection

The position detection subsystem is implemented using a 77GHz mmWave radar sensor Texas Instrument AWR1843Boost, a Raspberry Pi Zero 2 W single-board computer, and a USB power bank, shown in Figure 13, configured to measure the user's forward displacement and walking speed in real time. The system operates by detecting objects in front of the walker, identifying the closest valid reflection, and estimating motion parameters from the frame-to-frame measurements. These components are securely fitted in the front of the walker in a 3D printed electrical housing, showcased in 4.2.a. This system is selected over alternative sensing methods for several reasons: no dependence on lighting conditions, no mechanical contact required, ability to directly measure velocity using Doppler effect, and robust performance across different surfaces and environments.

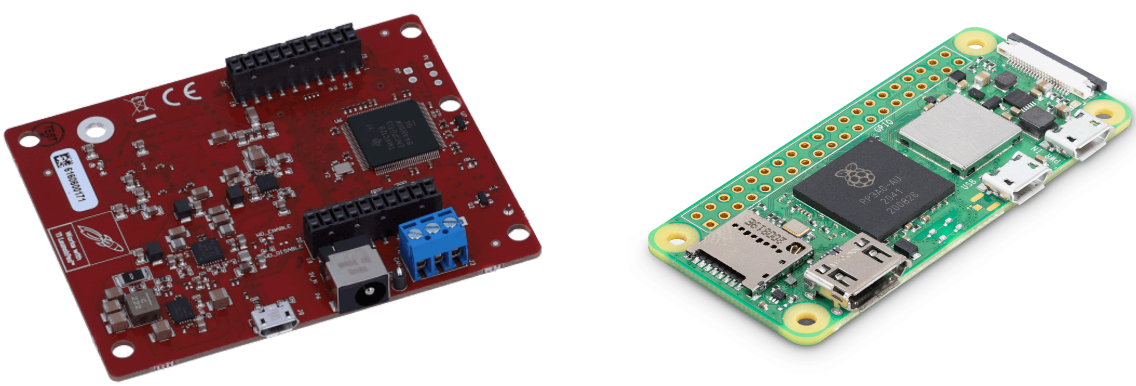


Figure 13: AWR1843Boost (left) and Raspberry Pi Zero 2 W (right)

The radar is using the TI xwr1843 mmWave Out-of-Box demo firmware flashed using CCStudio Uniflash and configured to a custom profile optimized for high range resolution and short-distance tracking, suitable for indoor walker use. Notable parameters are shown in Table 3. A sample scanning output is shown in Figure 14 in TI mmWave Demo Visualizer. The narrow field of view is critical because it filters irrelevant reflections from objects and focuses detection on the forwarding walking direction. The radar uses 3 transmit antennas and 4 received antennas, enabling multi-input multi-out (MIMO) processing for improved spatial resolution. The configuration also applies constant false alarm rate (CFAR) detection to identify valid targets while suppressing noise and cluster.

Range resolution	0.042 m
Maximum unambiguous range	9.94 m
Radial velocity resolution	0.04 m/s
Maximum velocity	1 m/s
Frame duration	100 ms
Asimuth field	±20°

Table 3: *Notable customized parameters applied on the radar*

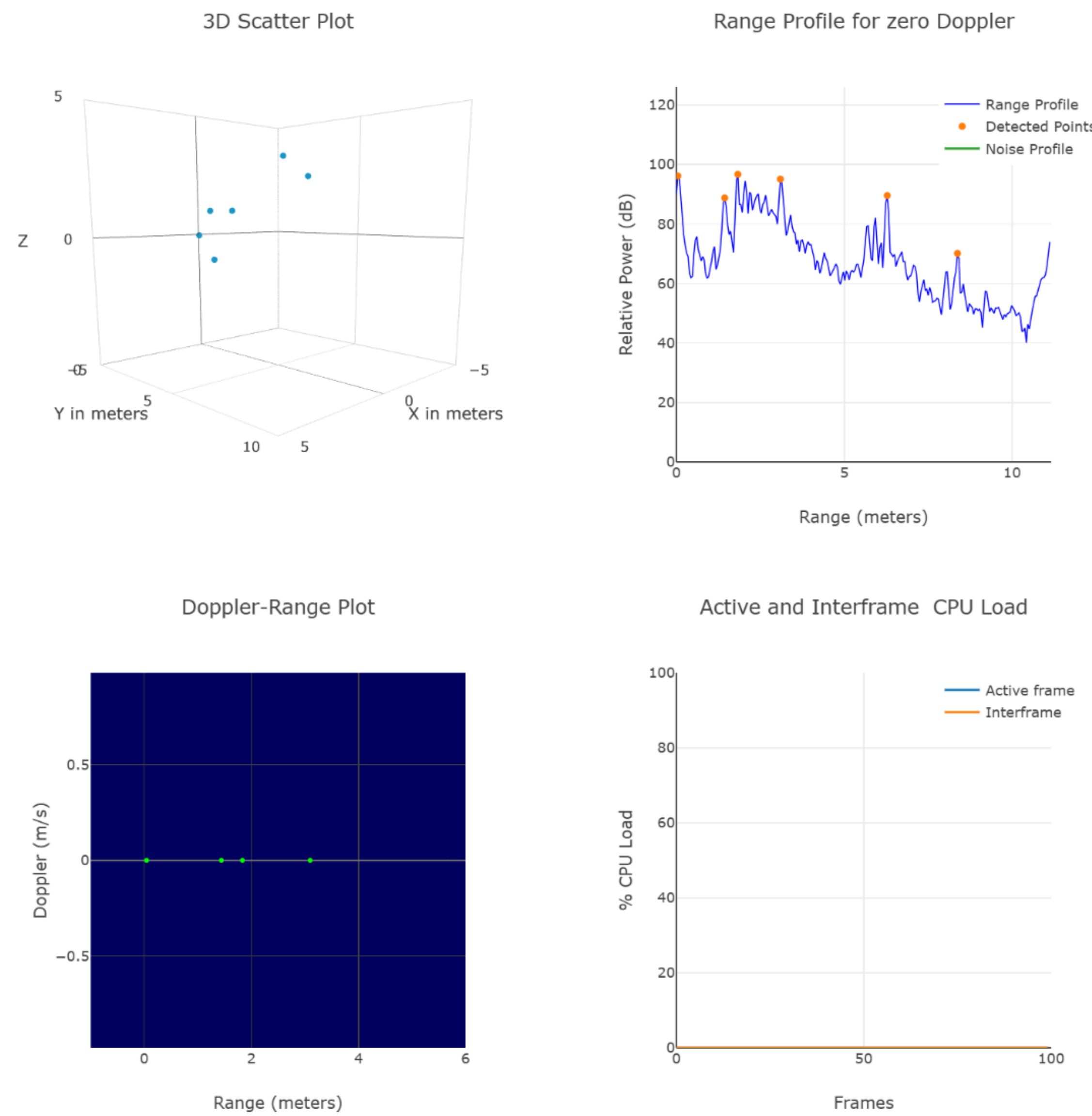


Figure 14: AWR1843Boost visualized sensing output

The radar outputs data through 2 UART interfaces: CLI port (115200 baud), sending configuration commands, and Data port (921600 baud), streaming binary detection data. Thus a Raspberry Pi Zero 2 W is used to cooperate with OOB firmware of the radar by sending configuration commands to the radar, continuously reading incoming binary data, and parse Type-Length-Value (TLV) structured packets into usable object data. This part of code and logic are derived from AWR1843-Read-Data-Python-MMWAVE-SDK-3 project by Ibai Gorordo [40], open sourced under MIT license. The controlling program runs on the pi as a system service, which automatically starts when pi is powered on and is connected to the radar on the micro-USB port (dev-ttyACM0.device and dev-ttyACM1.device). Thus the subsystem starts functioning automatically whenever the radar and pi are powered on.

The coming data stream to the Pi consists of frames containing the number of detected objects, object positions (x, y, z), and radial velocity. The system extracts the velocity of the selected closest object and computers walking speed, converted from meters per second to feet per second for display. Total distance travelled is computed through numerical integration. Time difference between frames measured using system timestamps and distance is accumulated incrementally.

The processed position data, which are distance and speed, are transmitted via BLE using a Raspberry Pi based server, with the same UUIDs as the load cells. The system is broadcasted as a peripheral device named SW-Radar.

All source codes are included in Appendix E.

3.3. Mobile Application

The smart walker mobile application was developed using SwiftUI for iOS and serves as the primary user interface for real-time monitoring, data recording, and post-trial analysis. The application connects wirelessly to three independent sensor modules via BLE, integrates their data streams, and presents clinically relevant mobility metrics to the user. The application is structured into three main functional layers: bluetooth communication, data processing and storage, and user interface. All source codes are included in Appendix E.

3.3.a. Bluetooth communication

The application uses the Core Bluetooth framework of Swift to manage simultaneous connections to three BLE peripherals: left foot module (SW-LeftFoot), right foot module (SW-RightFoot), and radar module (SW-Radar). Each device is identified by its advertised name and shares a common service and characteristic UUID. This unified design simplifies parsing and synchronization across devices. The BLE manager (BluetoothManager.swift) is responsible for scanning for available devices, automatically establishing and maintaining connections, automatically reconnecting upon disconnection, and receiving characteristic notifications at 200ms intervals. Figure 15 showcases the bluetooth status indicator on the app main page, which is color coded and reflects the connectivity of three sensors separately.

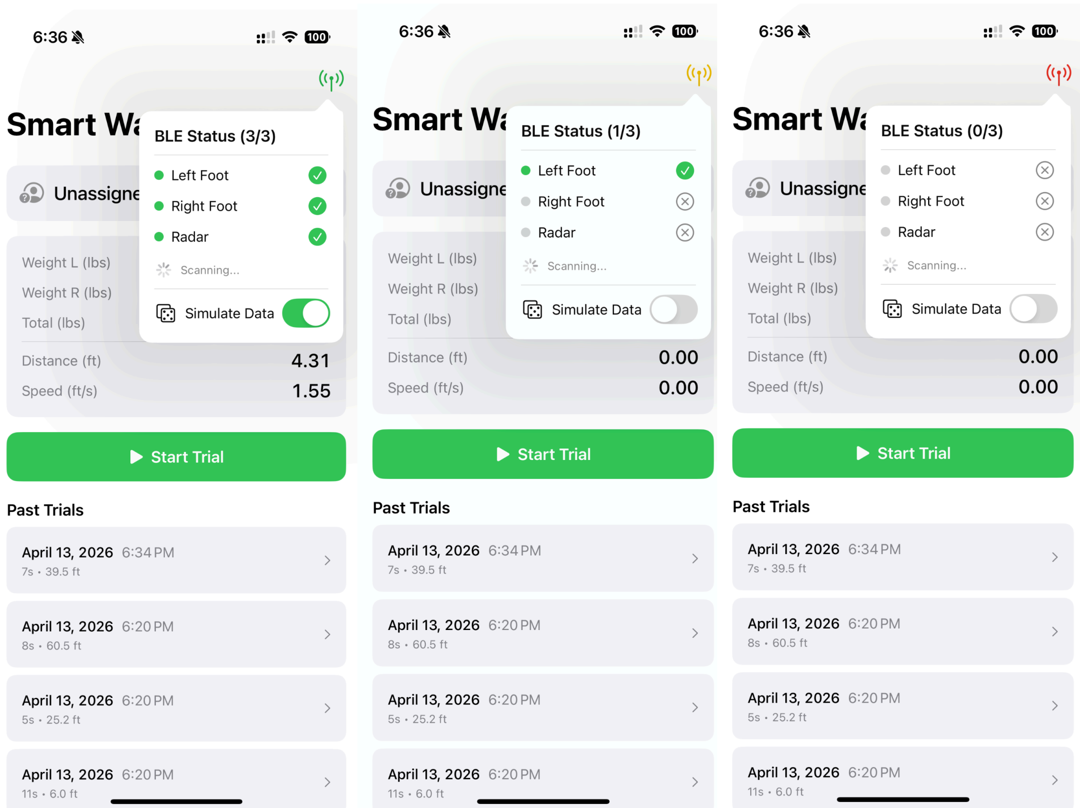


Figure 14,15,16: BLE connection status indicator

3.3.b. User interface

The main dashboard provides live visualization of key mobility metrics: total weight (lb) and left/right distribution, walking speed (ft/s), distance travelled (ft), and system connection status, shown in Figure 15.

The application includes a built-in trial recording feature to capture time-series data during walking sessions. The key features are one-tap start/stop recording, data sampling at 200ms intervals, live elapsed time display during recording, a trial list, and automatic association of trial with a selected patient, also shown in Figure 15.

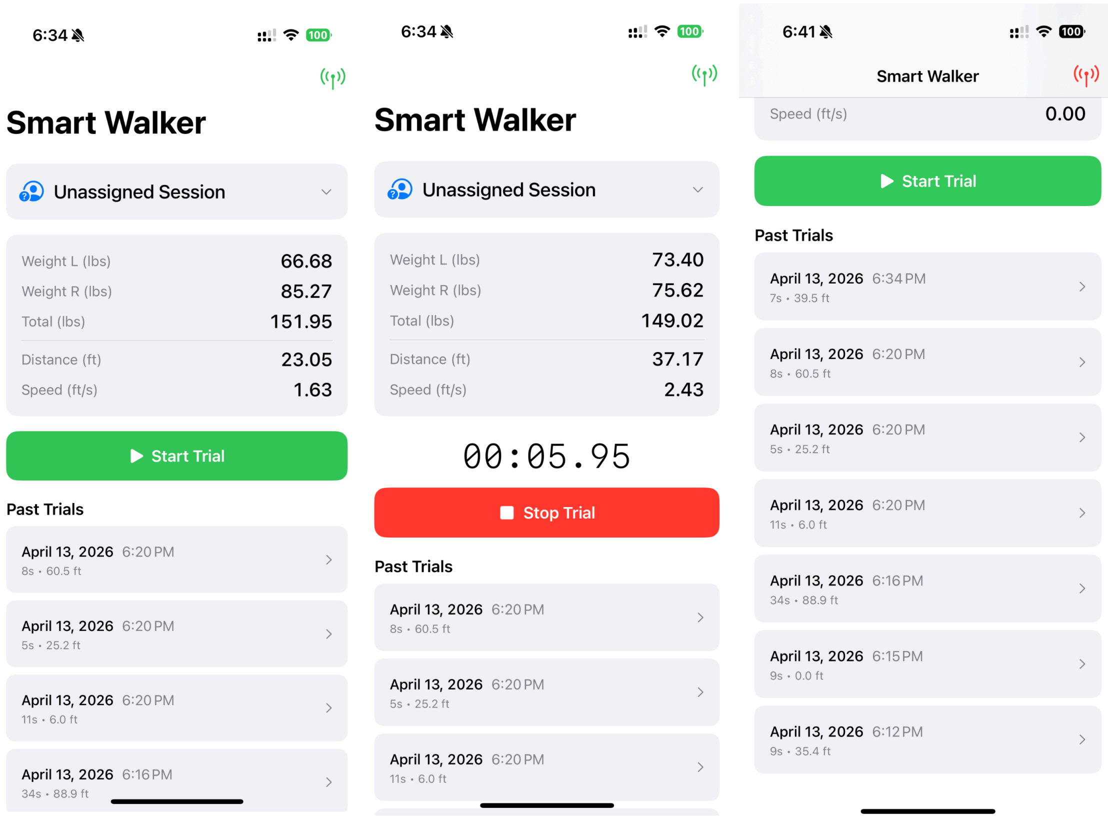


Figure 17: Main page of the app with a trial recorder

The application supports multi-patient usage through a structured data model. A patient list present, shown in Figure 16, to enable users to add and select patients, store multiple trials per patient, and organize and review historical data. All data is persisted locally using JSON storage, ensuring that patient and trial information is retained across app restarts without requiring external databases. That is, all patient related information will only be stored locally on the phone, without risk of leakage unless the user proactively exports and shares the data.

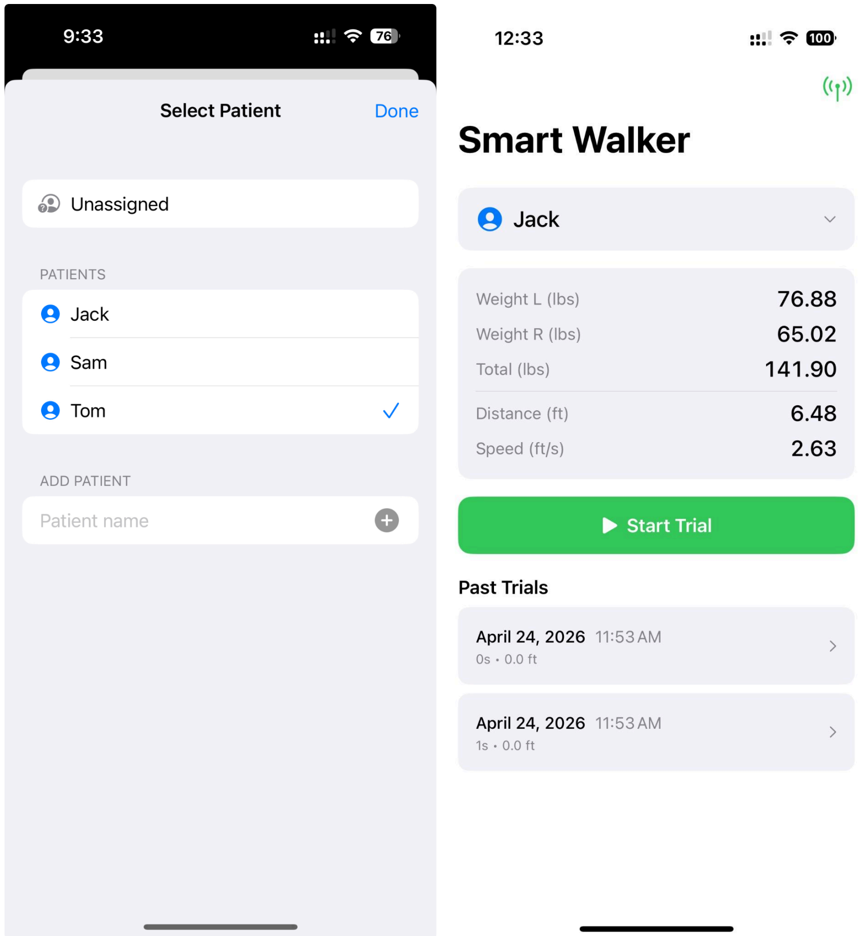


Figure 18,19: Patient list and patient-specific trial recording and storage

3.3.c. Data processing and storage

Incoming data from the three sensor modules are received asynchronously and merged into a unified data stream. Each update cycle includes left and right foot weight, distance travelled, and walking speed. These values are combined into a single structured data point and timestamped using the system clock. This ensures temporal alignment across all sensor modalities despite independent BLE transmission.

After a trial is completed, the application provides a detailed summary view, as shown in figure 17, including the total duration, total distance travelled, average walking speed, and average weight applied to the walker. Additionally, the application auto-generates 2 time-series plots based on these data records using Swift Charts framework: speed vs. time, and left and right weight vs. time. This visualization allows clinicians to assess gait consistency, symmetry, and rehabilitation process. Trial data can be exported as a CSV file through the iOS share interface, including all recorded time-series values. This enables external analysis in tools such as Excel or MATLAB, long-term tracking and documentation, and integration into clinical records.

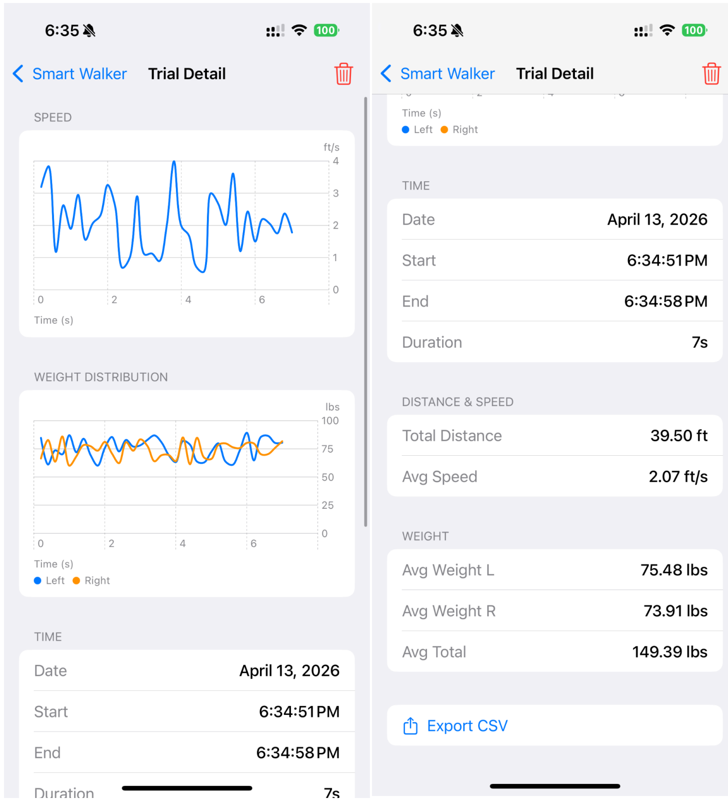


Figure 20: Trial detail page

4. Fabrication

The Smart Walker system was constructed by integrating two 100 kg compression load cells into custom 3D-printed end caps attached to the walker's rear legs. The end caps were modeled in CAD to securely house the load cells while maintaining structural alignment with the walker frame, fabricated using 3D printing, and attached via friction fit to allow tool-free installation and removal. Each load cell was connected to a dedicated SparkFun HX711 24-bit load cell amplifier, which interfaced with a Seeed Studio XIAO ESP32S3 microcontroller housed within the end cap assembly. The XIAO ESP32S3 processed the amplified load signal and transmitted bilateral load data wirelessly via Bluetooth to the iOS application.

The mmWave radar module (Texas Instruments AWR1843BOOST) was mounted within a separate central electrical enclosure clipped to the front leg of the walker frame, oriented at 90° relative to the direction of travel to ensure consistent wall-facing geometry during use. The radar was managed by a Raspberry Pi Zero 2W housed within the same enclosure, which received range and velocity data over a wired serial interface and relayed processed output to the iOS app via Bluetooth. The enclosure was designed to protect internal circuitry while maintaining accessibility for maintenance and future sensor upgrades. The system was powered by a 3.7V battery connected through an inline power switch.

The load cells were calibrated with known static weights to establish a force-to-voltage conversion factor, and multiple trials were conducted to verify linearity and repeatability. Distance measurements from the mmWave radar were validated against tape-measured values to assess baseline accuracy. The iOS app served as the unified clinician-facing interface, aggregating real-time bilateral load, walking distance, and gait speed data into a single dashboard.

4.1. Load Cell

Two 100 kg miniature compression load cells were integrated into the Smart Walker system to measure bilateral weight-bearing during gait. Each load cell operates on a Wheatstone bridge principle, generating a voltage differential proportional to the applied compressive force. The output signal from each load cell was routed through a dedicated SparkFun HX711 24-bit analog-to-digital amplifier, which amplified the low-level strain gauge signal to a level readable by the microcontroller. Each end cap assembly was paired with a XIAO ESP32S3 microcontroller, which handled analog data acquisition, onboard processing, and Bluetooth transmission of load data to the iOS application.

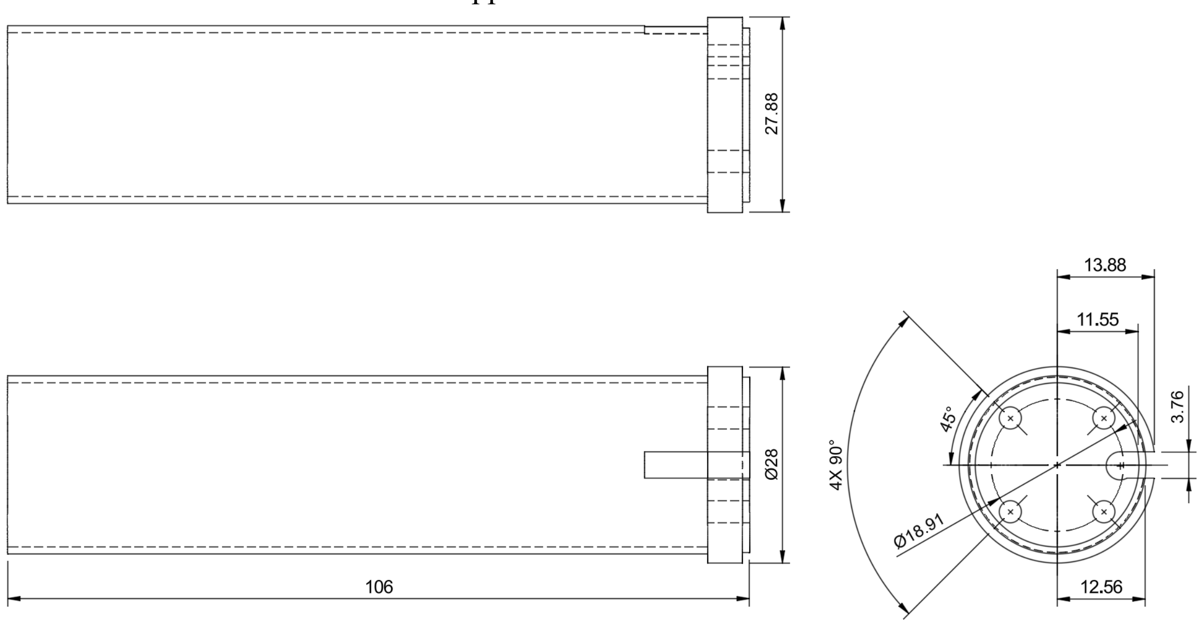


Figure 21: Walker foot circular housing CAD drawing

4.1.a. Load Cell Holder

The load cell housing was designed in CAD and 3D-printed in PLA. The housing consists of two components: a circular housing body and a plunger. The housing body has an outer diameter of 27 mm and a height of 27 mm, with four guide pins (Ø2.75 mm) arranged at 90° intervals on a pitch circle of Ø18.91 mm to constrain the plunger axially and prevent rotational misalignment under load. The plunger, which transmits compressive force from the walker leg down onto the load cell, has an overall length of

106 mm and an outer diameter of 28 mm, with a contact face geometry of 13.88 mm × 12.56 mm. The plunger inserts into the housing body and seats against the load cell surface, ensuring centered and repeatable force transfer. The assembled end cap attaches to the walker's rear leg via a friction fit, allowing tool-free installation and removal in accordance with the modularity requirements of the design.

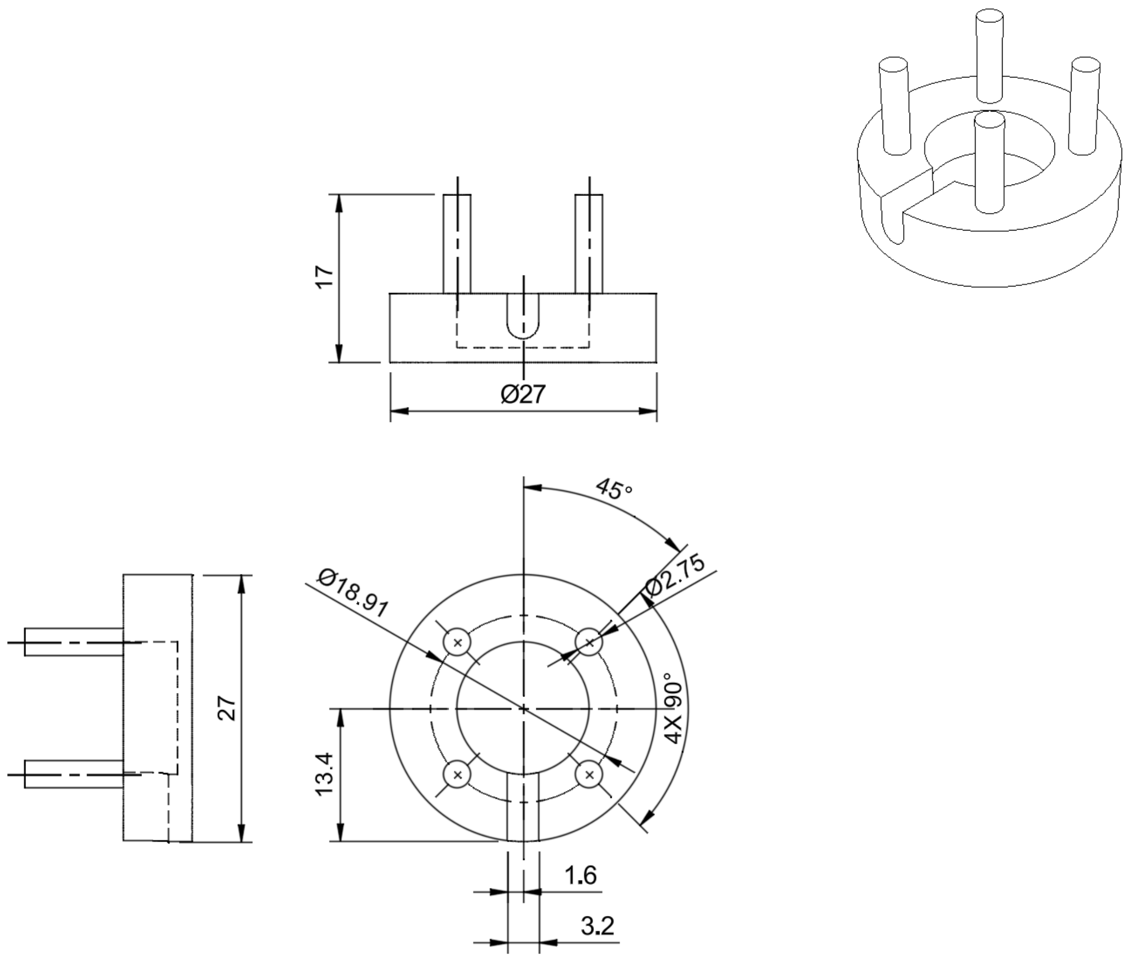


Figure 22: Load cell holder CAD drawing

4.2. mmWave Radar

The mmWave radar module selected for the final design is the Texas Instruments AWR1843BOOST, which uses frequency-modulated continuous wave (FMCW) signals in the 77–81 GHz band to measure the range and velocity of objects. The sensor emits RF signals from its TX antennas toward a wall-mounted reference target, and the reflected signals are captured by the RX antennas. The onboard digital signal processor computes the intermediate frequency (IF) signal from the mixed transmitted and received waveforms, from which range is mathematically derived via time-of-flight. The radar is mounted within the electrical housing, fixed to the interior front face, with a cutout in the housing wall exposing the antenna array to allow unobstructed signal propagation. The housing is clipped onto the front leg of the walker frame, and the housing is oriented at 45° relative to the walker's direction of travel to ensure consistent wall-facing geometry during use.

4.2.a. Electrical Housing

The electrical housing was designed in CAD and 3D-printed in PLA. The enclosure, as seen in figure 23 below, measures 197.5 mm × 122.5 mm × 80.95 mm externally, with a wall thickness of 15.5 mm on the side panel. An internal mmWave radar cutout measuring 85.52 mm wide × 28.02 mm tall is positioned at 32.22 mm from the housing edge to align with the radar antenna face. The housing attaches to the walker's front leg via a clip mechanism with a slot radius of R12.7 mm and an external clip width of 47 mm, providing a tool-free, lego-style connection that maintains the required 45° sensor orientation. The enclosure is designed to protect the internal circuitry from mechanical damage while remaining accessible for maintenance and future sensor upgrades

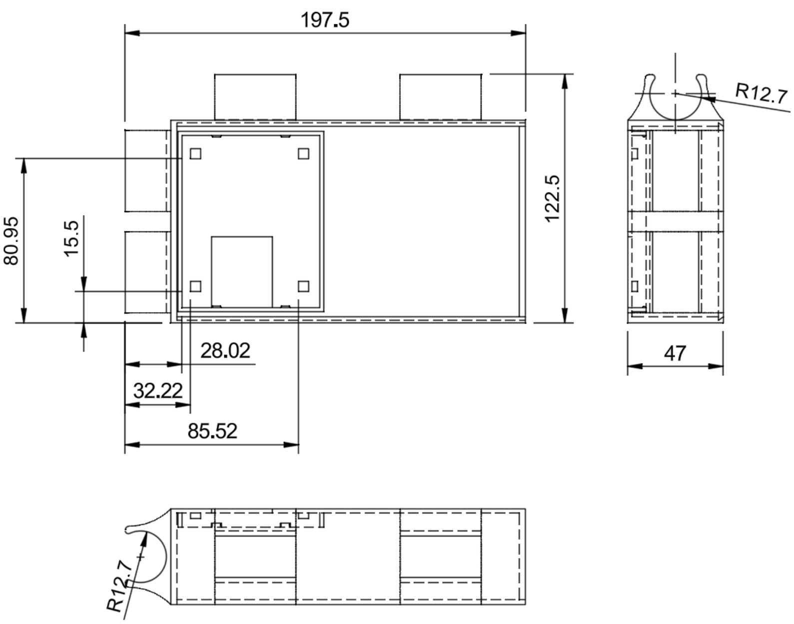


Figure 23: Electrical housing CAD drawing

4.3. Total Circuit

The complete Smart Walker circuit integrates the load cell subsystem, the mmWave radar subsystem, and a central processing unit into a unified data acquisition and transmission system. Each load cell is connected to a dedicated HX711 amplifier, which is wired to a XIAO ESP32S3 microcontroller housed within the end cap assembly. The XIAO ESP32S3 reads the amplified load signal, processes it, and transmits the data wirelessly via Bluetooth to the iOS Swift application. The mmWave radar is connected to and managed by a Raspberry Pi Zero 2W housed within the central electrical enclosure. The Raspberry Pi Zero 2W receives range and velocity data from the radar over a wired serial interface, and relays the processed output to the iOS app via Bluetooth. The iOS app serves as the unified display interface, aggregating real-time bilateral load, walking distance, and gait speed data into a single clinician-facing dashboard. The system is powered by a 3.7 V battery with an inline on/off switch, providing sufficient runtime for clinical session durations. All wiring between subsystems is routed along the walker frame and secured to minimize interference with patient movement.

5. Testing and Results

5.1. mmWave radar

As seen in Appendix D, this test is intended to validate that mmWave radar-based sensing can 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. [41]

Distances of 2-10m were tracked, as the client's standard walking distance test is the 10-meter walk test. The measured distances were tracked using the app, which was Bluetooth-connected to the phone, and the actual distances were measured manually and with the tracker analysis app. To visualize the mmwave radar accuracy results, we created a plot as shown in Figure 24, where the actual and measured distances from 2-10m are consistent, with a distance error of 5.7% m/m, which is within the range of our product design specifications. For distance measurements above 10m, the results had errors exceeding 50% m/m due to configuration issues in the mmwave radar code and were therefore not tested.

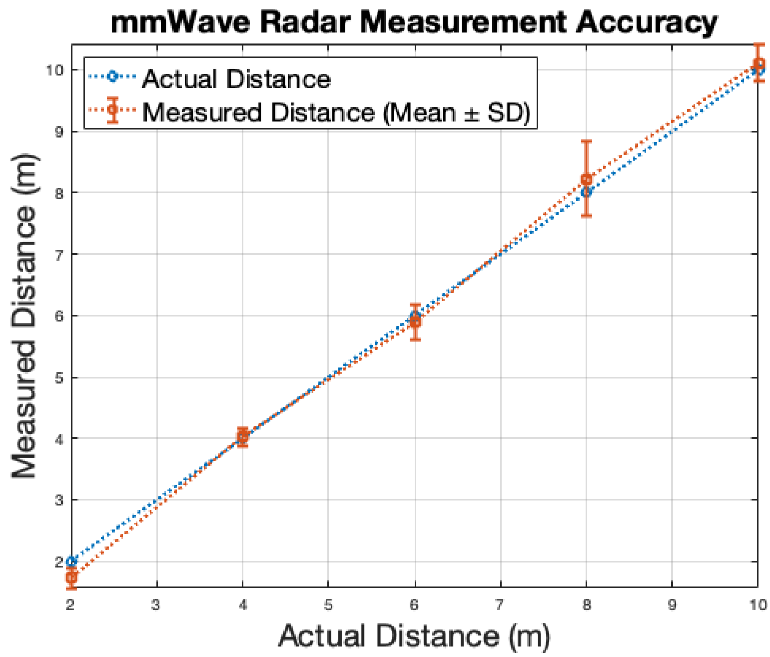


Figure 24: mmWave radar measured vs actual distance (mean ± SD) across the 2–10m

5.2. Load cell

As seen in Appendix C, the accuracy of the load cells will be evaluated by comparing their recorded values from the app to the known weights of 20 lb, 40 lb, 60 lb, 80 lb, 100 lb, 120 lb, 140 lb, 160 lb, and 180 lb. The load cells were tested using a calibration factor of 90367.5, obtained by comparing load cell readings against individually applied known weights. Load cells were placed in the load cell holder of each walker leg to prevent uneven loading. For each load level, the weight plates were placed centrally on the two sensors so that the applied force was evenly distributed across both sensors. After placing the weights, 10 seconds were allowed for the load cell reading to stabilize, and the load cell's output was recorded in the app. The paired load cell and reference readings from each trial were used to calculate percent error across the full operating range, allowing us to determine how well the load-cell system performs under controlled loading conditions. The measurements from each device will then be compared to assess the consistency of our data between these two measurement systems. To ensure accuracy, 3 trials will be conducted for each known weight.

To visualize the load cell accuracy results, we made a plot as shown in Figure 25, where the measured load stays consistent with the actual load up to 120lbs; after that, the readings level off, but they still meet the requirement of 100lbs per load cell. The average load error was 23.5% lb/lb, and 13.1% lb/lb up until 120lbs.

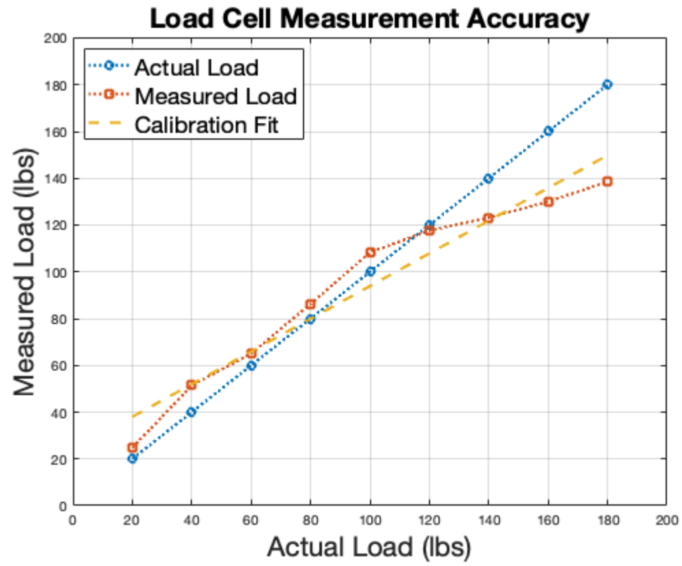


Figure 25: Load-cell measured vs actual load across the 20–180lb showing linear response.

6. Discussion

Based on the testing results, the feasibility and effectiveness of using the smart walker device in clinical settings were determined. It is important that load measurement, speed, and distance testing are accurate, as these are the key quantitative identifiers of the patient's rehabilitation progress and criteria that the client specifically requested. Speed was not a criterion that was a focus on during the testing procedure, as speed is obtained from the distance measured, so all testing reflects the distance traveled and load applied to the system. A 10-meter walk test is the standard metric for measuring a TBI patient's rehabilitation progress so the mmWave Radar was calibrated to record distances up to 10m, and the average measured distance error was 5.7%, which was within the acceptable range of error. The larger the distance record becomes, the larger the deviation from the literature error becomes. This is an issue that can be resolved when calibrating the mmWave radar, as the radar utilised has the capabilities to record distances up to 145m, however it all depends on the calibration in the code. The mmWave radar calculates distance mathematically based on the sweep rate, frequency band, and RX antenna gain, which are all components that can be adjusted in the code. One issue that was noted was that the mmWave radar's ability to penetrate through occlusions was not as strong as initially imagined. The environment in which the mmWave radar was tested was one with multiple occlusions present, and in scenarios with translucent occlusions, such as a holed fence, the data recorded was not accurate, as the radar could not sense the wall. Future work would include conducting more research into the occlusion sensing capabilities of the mmWave radar utilized.

The error associated with the load cells was greater than intended, an error of 14.7% was obtained. The load cells are extremely small in size, so placing the loads onto the load cells in a consistently uniform manner was a challenge. Future work would include adjusting the testing protocol of the load cells to develop a system to accurately and consistently place the loads onto the load cell in a uniform manner. When the smart walker is in use, any recorded data needs to be in accordance with HIPAA, to protect patient identity and confidentiality [42], which is the case for the design as all data transmitted to the app does not go via the internet, so there is no risk of a data leak associated with it.

All housing components were constructed out of PLA, however through constant attachment and removal from the walker, certain aspects of the components started to break, illustrating that 3-D printing the housing components out of PLA is not a viable choice for long-term housing components. Future work would be adjusting the materials utilised for the housing components to a more durable material, while keeping expenses in mind.

Potential sources of error in the testing process, related to inaccurate measurement of distance, can be due to signal blockouts caused by occlusions in the environment, resulting in lower values than expected [43]. Potential sources of error in load measurement could include uneven weight distribution and the manner in which each load was placed on top of the load cell. 3D-printed tolerances can also affect force transfer and electrical noise in the strain gauge amplifier. Moreover, when the load cell system is placed inside the walker leg, the walker legs are at an angle, so future works would include accounting for the slant of the walker leg and determining how that would affect the load that is being outputted, as the values currently obtained may not be the literature value of the actual load applied to the walker.

7. Conclusion

This project aims to provide neurorehabilitation physical therapists and traumatic brain injury patients with an accurate and convenient system to track real-time measurements of patient performance, specifically of speed, load, and distance, without altering the safety or function of a standard walker, as a way of measuring a patient's rehabilitation progress. Through research and testing, it was determined that a modified version of Smart Walker 2.0 should include a sensor combination of load cells to measure pressure, an mmWave radar sensor to measure speed and distance. These components provided accurate, reliable data while minimizing the walker's structural integrity, ensuring safety. An Arduino Uno WiFi Rev2 was used to connect WiFi and Bluetooth data transmission and ensure that the system is compatible with a variety of platforms.

The mmWave radar is extremely effective in recording larger distances and is extremely sensitive, so it would be able to record even minute changes in distance, and the testing error was within the acceptable range. Future works would include calibrating the mmWave radar to record greater distances, as well as improving the occlusion sensing capabilities of the radar. The compression load cells utilized are extremely sensitive as well, however a better and more consistent testing protocol will need to be developed to ensure a uniform placement between all the loads during testing, as the error obtained for load cell testing was higher than desired.

Multiple iterations of all the housing components were produced throughout the semester, including the electric housing for the mmWave radar, as well as the load cell housing system with the integrated end cap design. The integrated end cap designs proposes a new marketable concept to this design, with applications that go beyond measuring the rehabilitation progress of traumatic brain injury patients. Specific to fabrication, future work would include altering the materials utilised for the housing systems to make them more durable, as well re-soldering the load cell components to be a neater and more compact system. In addition, incorporating clinical trials and human subject testing with on-site patients can provide realistic feedback and help determine adjustments that need to be made, especially from an ergonomic standpoint.

8. Acknowledgements

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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

Client:	Dan Kutschera	dankutschera@gmail.com
Advisor:	Justin Williams	jwilliams@engr.wisc.edu
Team:	Nicolas Maldonado (Team Leader)	namaldonado@wisc.edu
	Navya Jain (BWIG & BPAG)	njain52@wisc.edu
	Shreya Venkatesh (Communicator)	svenkatesh9@wisc.edu
	Xicheng Yang (BSAC)	xyang622@wisc.edu

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,	081561703	1	$136.73	$0	Link

		Inc.					
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	

Appendix C: Load Cell Protocol

Aim: Test the weight capacity of our load cells (individually). To verify the accuracy of our calibrated load-cell system, we will compare its measurements with those from a digital reference scale with known accuracy. Both the walker and the reference scale will be placed on the same flat, level surface to minimize variation due to uneven loading. Each load cell will be tested, and data will be collected individually, as each has its own amplifier and Arduino system.

Materials:

- Load cell system (Load cell, amplifier, Arduino)
- Computer?
- Walker
- Rigid board - uniform loading platform
- Weights: 0lb, 25lb, 50lb, 75lb, 100lb, 125lb, 150lb, 175lb, 200lb

Protocols:
Data Collection from Load Cells

1. Lay the rigid board across the walker's handle grips to create a uniform loading platform; the board's weight will be measured on the reference scale beforehand and included in all load calculations.
2. Accuracy will be assessed using linear weight increments of 25 pounds, starting from 0lb up to 300lb. The load must be placed carefully and centrally on the board so that the applied force is evenly distributed across both handle grips.

3. Allow 10 seconds for the load-cell reading to stabilize, then record the walker's measurement.
4. Transfer the same weight setup, including the board, to the reference scale to obtain the true load value.
   a. Repeat this process for three full trials at each load increment to evaluate both accuracy and repeatability.
   b. Additional repeated measurements at a single mid-range load (such as 150 lb) will be collected to assess consistency over time.
5. The walker and reference readings from each trial will be used to calculate absolute error, percent error, and variability across the full operating range, allowing us to determine how well the load-cell system performs under controlled loading conditions.

Data Analysis for Data Collected from Load Cells

Once all measurements have been collected, we will analyze the load-cell system's accuracy by directly comparing the walker's recorded values to the corresponding readings from the reference scale at each 25-lb increment.

1. For each load level, the absolute error (walker reading minus reference reading) must be calculated, and the percent error relative to the true load must be reported. These calculations will be performed for each of the three repeated trials to determine the extent of variation in the readings under the same loading conditions.
2. Compute the mean error and standard deviation across trials for each load to evaluate the sensors' accuracy and repeatability.
3. To visualize performance across the full range, generate a plot comparing the walker's measured load to the reference scale values, as well as an error-versus-load plot to illustrate how measurement error changes with increasing weight.
4. The board's weight will be included in every data point so that the analysis reflects the true load applied to the system. If the mean percent error remains low and consistent across the 0–300 lb range and the variation between repeated trials is small, we will conclude that the load-cell system maintains reliable accuracy throughout its operating range.

Appendix D: mmWave Radar Protocol

Aim: To evaluate the accuracy and reliability of the mmWave radar system for distance measurement, the radar measurements were compared to position data obtained from Tracker motion analysis software using a calibrated video reference setup. This comparison allowed verification of radar performance under controlled motion conditions representative of expected walker operation.

Materials:

- mmWave radar sensor system (mounted in walker housing)
- Arduino data acquisition system
- Computer with serial monitor and Tracker motion analysis software installed
- Meter stick (for spatial calibration reference)
- Camera (fixed-position recording setup)
- Walker prototype
- Flat indoor testing area

Protocols:
Data Collection from Load Cells

1. Position the walker at the starting location within the camera's field of view.
2. Place a meter stick along the motion path so that a known 1-meter reference distance is clearly visible for Tracker calibration.
3. Begin recording video using the fixed-position camera before initiating walker movement.
4. Start the Arduino serial monitor to record mmWave radar distance measurements.
5. Push the walker forward along a straight path at a natural walking speed while the mmWave radar continuously records distance data.
6. Stop recording once the walker reaches the end of the motion path.
7. Repeat the walking trial three times to evaluate measurement repeatability.
8. Upload the recorded video into Tracker motion analysis software.
9. Calibrate Tracker using the visible 1-meter reference length from the meter stick.
10. Track the walker position frame-by-frame within Tracker to obtain ground-truth displacement data.
11. Export displacement measurements from Tracker for comparison with mmWave radar measurements.

Data Analysis for Data Collected from Load Cells

1. Align mmWave radar distance measurements with corresponding Tracker displacement values using timestamps or frame matching.
2. Compute absolute error between radar-measured displacement and Tracker-measured displacement for each data point.
3. Calculate percent error across all trials
4. Compute the mean percent error across all trials to determine overall radar accuracy.
5. Calculate the standard deviation of measurements across repeated trials to evaluate repeatability.

6. Generate a plot comparing mmWave radar displacement measurements to Tracker displacement measurements.
7. Generate an additional error-versus-distance plot to evaluate how measurement accuracy changes across the operating range.

Appendix E: Code repository

All code for this project is open-sourced under the MIT License. Since the source code would take up a significant amount of space in this report, only a link to the GitHub repository is included below.

https://github.com/F4llenDeath/smart-walker