Smart Walker: Biometric Neurorehabilitation and Mobility Assessment System

Preliminary Report, October 8, 2025

BME 200/300

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Abstract

Patients undergoing rehabilitation from traumatic brain injuries (TBI) often rely on a walker for mobility, especially while recovering from experiencing trauma. One problem that patients face during therapy is that progress is difficult to quantify. Without objective data, physical therapists cannot demonstrate improvement to patients or insurance providers, which limits motivation and financial support for care. The client, Dan Kutschera, has requested the development of an innovative walker system that provides accurate, measurable feedback on patient performance. The system will consist of devices that attach directly to a standard walker without altering the safety or function. Weight sensors will be integrated beneath the walker to measure the amount of support the walker provides to a patient, while lidar sensors track speed and distance traveled. Together, these features will allow therapists to evaluate rehabilitation progress with clear metrics. Testing will involve applying known weights and measuring controlled distances and speeds to ensure accuracy and reliability. By developing a walker that provides both quantitative feedback and clinical reassurance, this project aims to enhance rehabilitation outcomes and equip therapists with data to support patient confidence and facilitate accurate insurance documentation.

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Introduction

Motivation

Patients with traumatic brain injuries often undergo traumatic events followed by intense rehabilitation to help them walk and return to everyday life as soon as possible. Acute stroke care clinics provide specialized care to initiate recovery following hospitalization [6]. During rehabilitation, doctors struggle to measure progress as patients gain strength, making it difficult for physicians to provide patients with tangible data of their improvement. The insurance companies also require evidence of improvement, which necessitates that clinics document progress to be reimbursed for the services they provide. The smart walker will measure the pressure applied, speed, and distance walked of patients with neuro-rehabilitation needs. This data will be reported and displayed in real-time to help clinicians monitor progress and motivate patients. Ultimately, the device will reduce the time required to meet Medicare's documentation needs and increase objective markers of patient readiness for discharge [7].

Existing Devices

Currently, there are no commercially available devices that fully meet these clinical and functional requirements. An example of an adapted smart walker is the Camino, which is an AI-equipped device that offers features such as automatic braking and power-assisted motion [1]. Several issues arise with the Smart Walker, as the Camino is priced at approximately $2,999, which places it well beyond the budget of most rehabilitation clinics. Additionally, it's not designed for use in clinical settings, limiting its applicability in structured rehabilitation environments. The fact that there are no better commercially available devices highlights the need for a cost-effective, clinically focused smart walker that can provide accurate, real-time data to both patients and clinicians.

Problem Statement

Mr. Daniel Kutschera, a physical therapist specializing in neuro-rehabilitation, requires objective, real-time data on walker use to guide therapy and meet the documentation requirements mandated by Medicare. Today, these metrics are gathered manually (using a wheel and a stopwatch), which does not quantify load, making measurements inconsistent and difficult to track. Earlier attempts to add sensors by modifying frames have compromised the safety and usability of the walker. This demonstrates a need for a small, lightweight, clip-on module for standard walkers that displays speed, distance, and the amount of weight the user applies to the walker in real-time, saves a brief session summary after each use, and doesn't alter how the walker is used or folded. Our budget to complete this is $500.

Background

Following a traumatic brain injury (TBI), walking speed is often referred to as the "sixth vital sign" because it provides an objective measure of functional recovery [2]. Gait speed encompasses the combined performance of multiple physiological systems, including balance, coordination, and muscle strength. Along with speed, the pressure applied to a walker is an essential indicator of patient stability, confidence, and weight-bearing ability, all of which are used to assess readiness for discharge from inpatient care [8]. Currently, the most effective methods for clinicians to measure progress are manual, involving the use of stopwatches and tape measures to record speed and distance; however, there is no reliable way to record pressure data. There are many problems with this method; it is time-consuming, subjective, and lacks real-time feedback. A system that continuously measures walking speed, distance, and applied pressure would allow for faster and more objective assessment of a patient's progress during rehabilitation.

To address this clinical need, we have been tasked with developing a device that incorporates integrated sensors to measure pressure, speed, and distance without compromising the walker's structural integrity. Previous versions of this project at UW-Madison have failed due to instability in the custom walker's frame, creating liability and safety risks. Our new design will focus on non-invasive, removable attachments that are accurate, consistent, and easily sanitized for use in a clinical environment. The attachments must be compact and lightweight, compatible with other existing two-wheeled walkers, and capable of repeated use.

Key Design Specifications (see full PDS in Appendix):

- Tracks pressure, speed, and distance accurately and consistently
- Reliable for at least 10 meters of travel and 30 minutes of use
- Removable and compact attachments that do not interfere with the walker
- Easily sanitized between patients
- Compatible with existing two-wheeled walkers
- Supports up to 140 kg (≈300 lb) of patient weight [3]
- Follow all ISO/FDA legal standards [4][5]

Preliminary Designs

Design 1: Tennis Baller

The Tennis Baller design utilizes a pancake load cell encased in a custom 3D-printed piece. It has a larger base for added stability while in use and is installed by placing it onto the end of one of the walker's back legs, replacing the existing end cap. Then, when the patient puts force on the walker, the load cell will measure the ground force as a way of measuring the weight being placed on the walker.

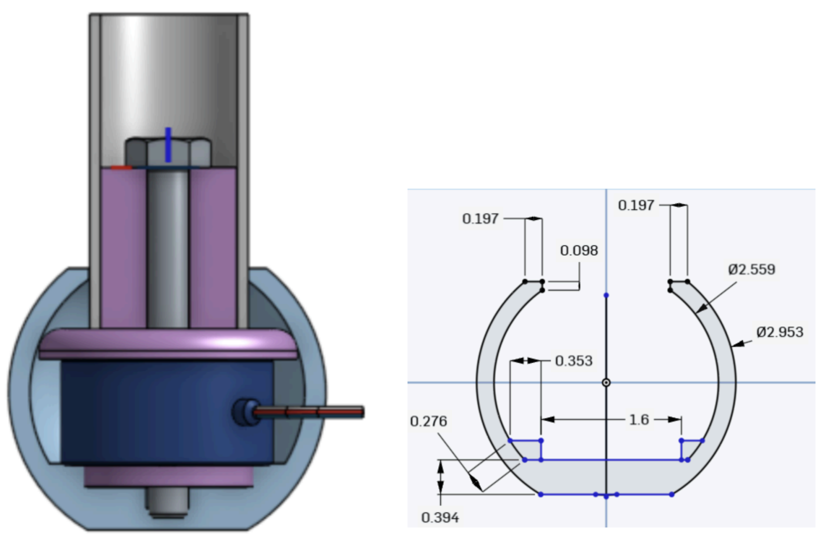


Figure 1: *Tennis Baller CAD Model and Dimensions*

Design 2: Endcap 2.0

The End-Cap design utilizes a load cell housed inside a custom 3D-printed end cap. It is used by placing the device on the end of one of the walker's back legs, replacing the existing end cap. When the patient puts weight on the walker, the load cell measures the ground reaction (vertical) force, which we use to determine the weight being applied to the walker. The point of this design is that it only slightly differs from the current end caps already incorporated into the walker, keeping it as similar as possible, with just the slight modification of fitting the load cell into the end cap as well.

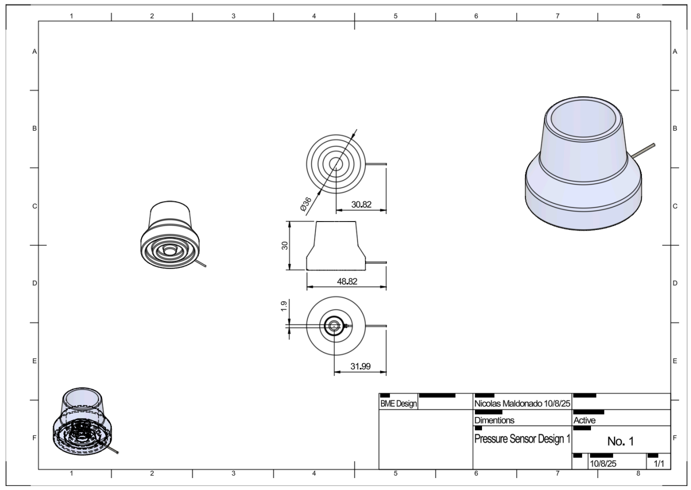


Figure 2*: End-Cap 2.0 CAD Dimensions*

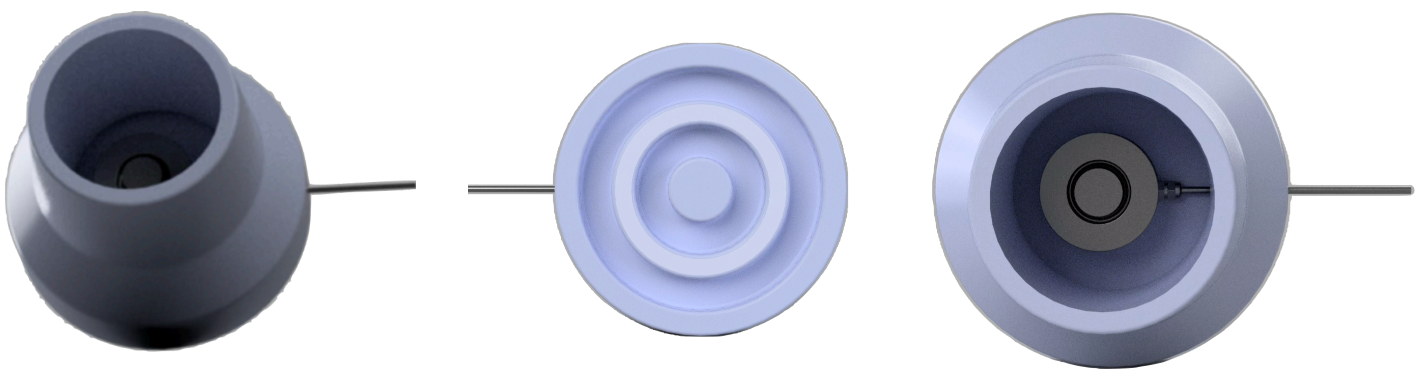


Figure 3: *End-Cap 2.0 CAD Models*

Design 3: Hand Gripper

The Hand Gripper design uses a load cell sandwiched inside a 3D-printed double-shell clamp that wraps around the walker's grips. It installs on the handles (one unit per side). When the patient presses on the handles, the load cell measures the force applied at each hand. If we add the two readings, we get the total weight the patient is putting on the walker.

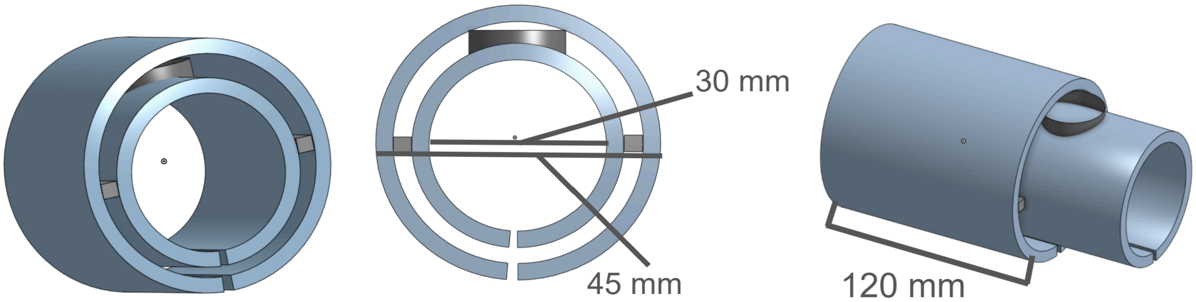


Figure 4: *Hand Gripper CAD Design and Dimensions*

Preliminary Design Evaluation

Design Matrices

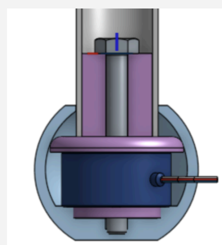
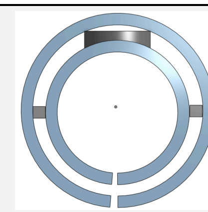
		 1. Tennis Baller		 2. End-Cap 2.0		 3. Hand Gripper	
Criteria	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Accuracy of Data	25	5/5	25	5/5	25	3/5	15
Simplicity	25	4/5	20	5/5	25	4/5	20
Usability	20	5/5	20	5/5	20	3/5	12
Safety	15	4/5	12	5/5	15	3/5	9
Ease of Set-up	15	3/5	9	3/5	9	5/5	15
Total (Out of 100):		86		94		71	

Table 1: *Design Matrix Load Cell Housing*

Accuracy of Data (25):
Both the Tennis Baller and End-Cap 2.0 received a full score of 5/5, demonstrating that these designs can reliably measure weight distribution and walking metrics without significant error. The Hand Gripper, however, received a 3/5, as its accuracy is compromised if the user squeezes the handle incorrectly. This makes the Hand Gripper less reliable for collecting consistent rehabilitation data.

Simplicity (25):
The End-Cap 2.0 scored the highest with 5/5 due to its straightforward design and ease of integration onto the walker. The Tennis Baller also performed well, earning 4/5, though its slightly more complex structure makes it less seamless. The Hand Gripper also scored 4/5, but its added components make it less intuitive for consistent use.

Usability (20):
Both the Tennis Baller and End-Cap 2.0 scored perfectly (5/5), as they can be used naturally during walking without altering how a patient interacts with the walker. The Hand Griper only scored 3/5 due to its reliance on the squeezing action, which could decrease stability and make the walker less functional in real-world rehabilitation settings.

Safety (15):
The End-Cap 2.0 received the top score of 5/5, since it maintains complete surface contact with the floor and does not compromise walker stability. The Tennis Baller followed with a 4/5, as it reduced the surface area, which could increase the risk of tipping. The Hand Gripper scored the lowest (3/5), as its design could compromise grip stability and lead to safety concerns during patient use.

Ease of Set-up (15):
The Hand Gripper scored the highest (5/5), since it can be easily attached without extensive modifications. Both the Tennis Baller and End-Cap 2.0 scored 3/5, as they require more effort to install correctly on the walker's legs.

Total Scores (100):
The End-Cap received the highest score of 94/100, primarily due to its strong accuracy, simple design, and easy integration with the walker. Then the Tennis Baller was given a slightly lower score of 86/100 because, although it performed similarly in accuracy and usability, it scored lower in safety due to its reduced surface area on the bottom of the walker, which has the potential to make it less stable. The Hand Gripper received the lowest score of 71/100 because even though it will be easy to attach, it will cause a decrease in grip stability and could produce inaccurate data readings if squeezed incorrectly, which lowered its safety and usability scores.

Overall, the End-Cap design was our best choice due to its reliability, simplicity, and compatibility with existing walker components.

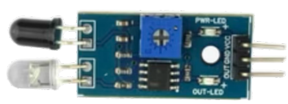
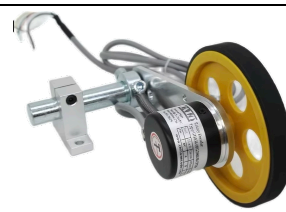
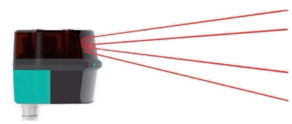
		 1. Infrared Sensor		 2. Rotary Encoder		 3. Lidar Sensor	
Criteria	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Accuracy of Data	25	3/5	15	5/5	25	4/5	20
Structural Impact	20	4/5	16	1/5	4	5/5	20
Safety	15	5/5	15	3/5	9	5/5	15
Reliability of Sensors	15	3/5	9	5/5	15	4/5	12
Ease of Set-up	15	3/5	9	1/5	3	4/5	12
Cost	10	5/5	10	3/5	6	2/5	4
Total (Out of 100):		74		62		83	

***Table 2**: Design Matrix Movement Sensors*

Accuracy of Data (25):
The rotary encoder scored the highest (5/5) for accuracy, as it provides precise measurement of distance and rotations. The lidar also performed strongly (4/5), offering accurate distance and speed tracking with minimal error. The infrared sensor scored the lowest (3/5), as it is less consistent and can be influenced by environmental conditions.

Structural Impact (20):
The lidar scored best (5/5) because it mounts externally and does not interfere with the walker's stability or structure. The Infrared sensor also performed well (4/5), being small and lightweight, although it still affected the structure more than the Lidar, due to its position next to the wheels.

The rotary encoder scored lowest (1/5), as it requires direct attachment to a wheel, which compromises structural simplicity.

Safety (15):
Both the lidar and infrared sensors scored 5/5, as they pose minimal risk to walker safety. Their designs allow for minimal change to the critical areas of the walker. The Rotary Encoder scored 3/5 due to its mechanical integration, which introduces potential hazards if not properly secured.

Reliability (15):
The rotary encoder scored the highest (5/5) since it provides consistent, reliable readings. The lidar followed with a strong 4/5 rating, although it can be sensitive to reflective surfaces. The Infrare sensor scored the lowest (3/5), as it is prone to inaccuracies depending on the lighting and surface conditions.

Ease of Set-up (15):
The lidar (4/5) and infrared (3/5) are both relatively simple to attach without significant modifications. The rotary encoder scored the lowest (1/5), since it requires precise mechanical integration that complicates the setup.

Cost (10):
The infrared sensor scored the highest (5/5) as the most affordable option. The rotary encoder scored moderately (3/5), while the lidar scored the lowest (2/5), reflecting its significantly higher cost.

Total Scores (100):
Overall, the lidar scored the highest with a score of 83/100 due to its strong accuracy/reliability, minimal structural impact, and straightforward setup. One of its main drawbacks is its high cost. Infrared placed second with a score of 74/100 because it is cheap, safe, and low-impact, but only has moderate accuracy/reliability. Lastly, the rotary encoder had the lowest score of 62/100. This is because, although it offers the best accuracy and reliability, its downsides include its structural impact, setup complexity, and some safety concerns. Overall, lidar offers the best total performance despite its high cost.

Proposed Final Design

The final prototype we have decided on, after reviewing the design matrix, is a combination of the lidar sensor and a design modeled after the End-Cap 2.0. The lidar will be mounted near the handlebars and points forward to read the distance to a wall or object. We calculate speed by measuring how the distance changes over time. The placement stays out of the user's way and does not change how the walker is used. The End-Cap 2.0 add-ons will wrap around the walker leg and tighten in place, so it is secure and easy to remove. A Lego-like insert fits inside the leg and presses on a load cell. This creates a direct force path, improves consistency, and keeps the footprint close to a standard tip.

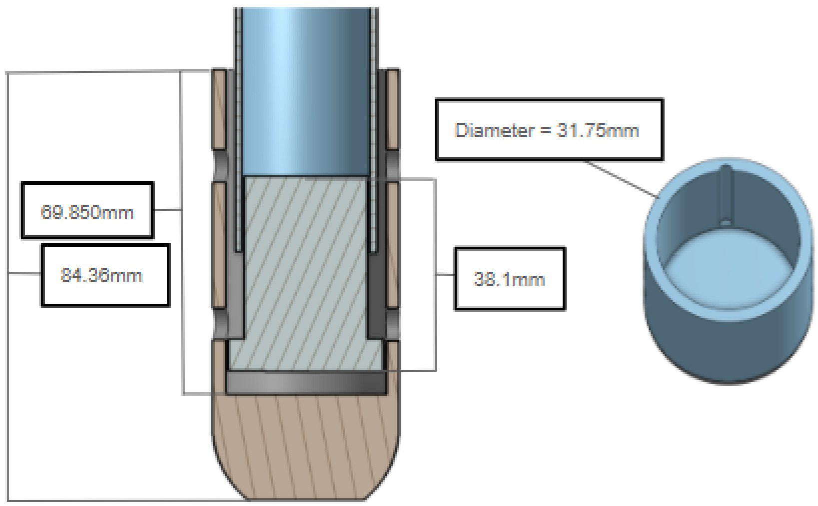


Figure 5: *End-Cap 2.0 CAD drawing with dimensions.*

Figure 6: *End Cap 2.0 initial prototype*

Fabrication

Fabrication will consist of three main categories: 3D printing, circuitry and coding, and attachment/integration to the walker. The end caps will be 3D printed using Thermoplastic Polyurethane (TPU), as it closely resembles the material currently used for the end caps. Polylactic Acid will be used to 3D print the electrical housing unit, which will be attached to the crossbar using rubber-cushioned metal cable clamps. The microprocessor used for this project is the ARDUINO UNO WiFi REV2. This will process the signals from the sensors and, with the WiFi or Bluetooth capabilities, can be connected to the clinician's computer or phone to view the data. The Garmin LIDAR-Lite Optical Distance Sensor - V3 will be used to measure the distance from the walker to the wall, and the device will be programmed to extract speed from this measurement. The two load sensors will work by deforming under the pressure of the walker user, changing the electrical resistance measured by the Wheatstone bridge circuit, producing a voltage proportional to the force. This will be accompanied by a load cell amplifier HX711, which allows for the weight to be read easily from the load cells. Because this design includes two load cells instead of four, a half-bridge configuration will connect them to the amplifier.

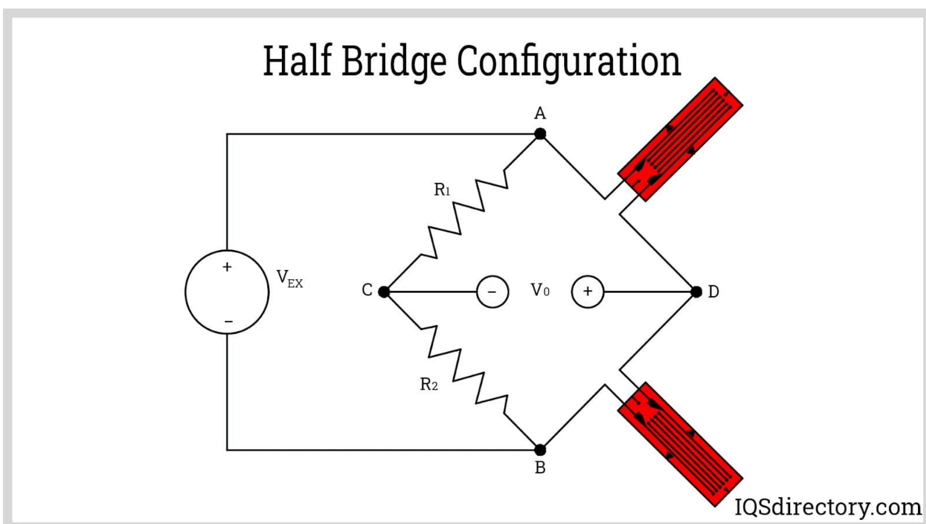


Figure 7: Half wheatstone bridge configuration showing strain gauges in red [9].

A KBT 12V 2400mAh Rechargeable Lithium-ion Battery will serve as the power source for the device. Figure 7 below shows a schematic of the circuit and components of the design [9].

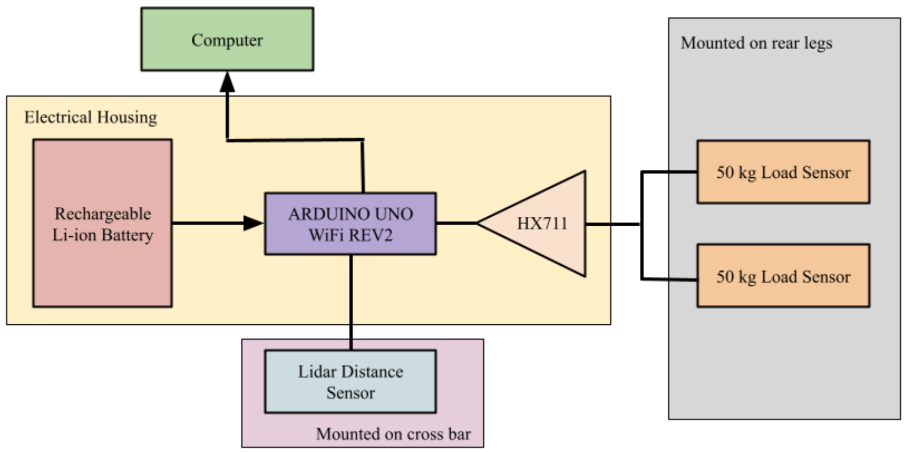


Figure 8 *Circuit block diagram of design and components.*

Testing and Results

Load 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 300 lbs) 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.

Speed Testing: We will be testing to validate both the average and instantaneous velocities. This will be done by marking ten distinct points one meter apart. Then someone will walk with the walker from the first marking until the end, while we record a video of this occurring. We will then view the video and record the walker's movement over each marked distance to get the velocities at ten different points during the trial. This will then be compared to the values the walker gives over the duration of the walk. We will then also compare the overall average speed to the average speed the walker reports, using the same markings and video. Multiple trials will be conducted to collect more accurate data.

Distance Testing: The accuracy of the distance measurements will be evaluated using a similar procedure to the speed testing protocol. Using two pre-set marked points, potentially the ten meters established during the speed testing. The distances recorded by the walker will be compared to the known total distance traveled. This comparison will enable us to evaluate the walker's distance-measuring capabilities. Multiple trials will be conducted to collect more accurate data.

Conclusion

The client requested the development of a device that could provide accurate, real-time measurements of patient performance during rehabilitation, specifically tracking pressure, speed, and distance without altering the safety or function of a standard walker. Through evaluation of multiple design options, a modified version of the End-Cap 2.0 load cell housing and Lidar sensor combination emerged as the most effective solution. These components provide accurate, reliable data while minimizing structural impact and preserving the walker's usability and safety.

The proposed design will enable clinicians to measure patient progress objectively, thereby enhancing both patient motivation and compliance with Medicare documentation requirements. The device is compact, removable, and easily sanitized, making it appropriate for use in a clinical setting. Fabrication will focus on lightweight, durable materials, and testing will confirm the accuracy of pressure, distance, and speed measurements under controlled conditions.

This project has the potential to transform the way rehabilitation progress is tracked by providing clinicians with quantitative data, thereby reducing their reliance on subjective or manual methods. Future work will focus on refining fabrication, conducting rigorous testing, and integrating data transfer to enable clinicians to assess their patients on-site. By providing therapists with a cost-effective and clinically focused tool, the smart walker aims to enhance rehabilitation outcomes and support both patient recovery and healthcare documentation needs.

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Appendix

Appendix I: Product Design Specifications

Function/Problem Statement:

Patients with TBI often undergo traumatic events followed by intense rehabilitation to help them walk and return to everyday life as soon as possible. During rehabilitation, doctors struggle to measure progress as patients gain strength, making it difficult for physicians to provide patients with tangible data of their improvement. The insurance companies also often do not feel that there is enough evidence of improvement, making it harder for the clinic to be paid for the services they provide. The smart walker will measure the pressure applied, speed, and distance walked of patients with neuro-rehabilitation needs. This data will be reported and displayed in real-time to help clinicians monitor progress and motivate patients. Ultimately, the device will reduce the time required to meet Medicare's documentation needs and increase objective markers of patient readiness for discharge.

Client requirements:

The device must provide real-time data on user pressure, speed, and distance. It must be compatible with the walkers currently being used without compromising the structural integrity of the walker. Data provided by the smart walker should be presented in a metrics report that is comprehensible to insurance companies. Furthermore, the client requested a compact design that is easy to use, accurate, and reliable. The budget for this project is ~$500.

Design requirements

1. Physical and Operational Characteristics
    a. *Performance requirements*
        i. The smart walker attachments will modify an existing clinical walker, which can support a patient weighing up to 140 kg.
        ii. The added attachments should not interfere with the original walker's function.
        iii. The metrics provided by the walker attachments will include distance, speed, and pressure, and should be recorded and displayed to both the user and clinician.
    b. *Safety*
        i. The structural integrity of the existing walker must not be compromised
        ii. The device must follow all of the neuro-rehabilitation facility’s safety standards and regulations

    iii. ISO requirements must be followed for all electronic and battery components[4].
    iv. Clear instructions should be given on how to use our walker attachments

c. *Accuracy and Reliability*
    i. The walker attachment should accurately measure the values of distance, speed, and pressure within 10% of absolute values.
    ii. The measurements should also not vary more than 5% from their measured values.
    iii. These metrics must be accurate over distances of 10 meters and over time periods of 30 minutes.

d. *Life in Service*
    i. The walker should withstand up to 10 patients for up to 5 trials a day over a period of 10 years before requiring maintenance.

e. *Shelf Life*
    i. The walker attachment is expected to last 10 years before requiring repair or part replacement.

f. *Operating Environment*
    i. The walker will be used at the client's neurorehabilitation center, which will be at a temperature of 16-26 °C. It is designed for indoor use and should not be taken outside to prevent damage from outdoor conditions.
    ii. 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.
    iii. The walker should be able to withstand up to 140 kgs (~300lbs) of pressure for up to 20 minutes at a time. The attached pressure devices should be able to withstand this pressure and accurately read a pressure of this magnitude [5].
    iv. The attachments to the walker should be able to be moved to different walkers.

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 can be switched between walkers if needed [6].

h. *Size*
    i. The size of the smart walker attachments should not impact the usability of the existing walker.

ii. The components should not protrude from the existing walker by more than 10 cm to ensure that the walker can still easily fit through doorways and can be stored effectively.

i. *Weight*

    i. The walker attachments should not add significant weight to the preexisting walker.
    ii. Clinical walkers typically weigh between 4.5 and 9 kg; therefore, the combined weight of the smart walker attachments and the walker itself should not exceed this range [7].

j. *Materials*

    i. Walkers are typically made of Aluminum with vinyl handles, serving as the base for smart walker attachments.
    ii. The attachments will include various electrical components and a display.

k. *Aesthetics, Appearance, and Finish*

    i. The smart walker attachments should be as non-invasive as possible to ensure the look is as close as possible to that of a regular walker. This will ensure that it is easy to use for patients and clinicians.
    ii. All wires should be contained to protect the device's lifespan and improve patient usability.
    iii. All data should be displayed in a way that is accessible to both patients and clinicians, and provide real-time updates to motivate improvement.

2. Production Characteristics

    a. *Quantity*

        i. There will be attachments for one walker, which include four pressure sensors, a device to measure speed and distance, and a display. All attachments should be removable and switchable between walkers.

    b. *Target Product Cost*

        i. The Budget for this project is $500

3. Miscellaneous

    a. *Standards and Specifications*

        i. FDA 21 CFR Part 820 (Quality System Regulation / QMSR):
            1. Specifies quality system requirements for medical devices, including design control, production processes, and corrective actions. FDA's new QMSR aligns this regulation with ISO 13485:2016, which will govern the design and manufacturing of Class II medical devices such as the Smart Walker.
        ii. IEC 60601-1-2:2014 – Electromagnetic Compatibility (EMC):
            1. Specifies requirements to ensure the Smart Walker's sensors and circuits are immune to electromagnetic disturbances and do not

emit interference that could affect other devices in home or clinical environments.

iii. ISO 11199-2:2005 – Assistive products for walking, Part 2: Rollators:
    1. Specifies performance and safety requirements for walkers with wheels, including stability, braking systems, strength, fatigue resistance, and labeling. Ensures the device meets international expectations for durability and safety.

iv. ISO 11199-1:2021: Assistive products for walking — Walking frames — Requirements and test methods
    1. This standard outlines the performance, safety, and durability requirements for walking frames, including our Smart Walker. This includes the load, fatigue, and stability testing. This is intended to ensure that walkers and any add-ons do not compromise user safety or functionality.

v. ISO 14971:2019: Medical devices — Application of risk management to medical devices
    1. This standard defines a structured process for identifying hazards, estimating and evaluating risks, implementing control measures, and monitoring effectiveness. This standard is essential for documenting and managing risks associated with various components of our Smart Walker, including structural failure, inaccurate weight data, and electrical hazards related to the add-on.

b. *Customer*

i. The metrics should be displayed live to motivate users and aid in recovery as efficiently as possible.

ii. The smart walker attachments are designed to attach to a 2-wheeled walker, as most patients are already familiar with the operation of this type of walker.

iii. A display should be located near the handles, allowing patients to see it while using the device.

iv. Since the users of this device reside in the U.S., all units need to be reported in empirical units to make it easier for patients to understand

v. All wiring and battery components need to be enclosed to protect user safety.

c. *Patient-related concerns*

i. The requirements must be removable and sanitizable, as a variety of patients will use them.

d. *Competition*

i. Few walkers on the market have similar features to what Mr. Kutschera is looking for in this walker. Some designs record speed, but there is nothing on the market that effectively records the pressure exerted by the patient on the walker.

ii. All known walkers are also extremely expensive and unreasonable for what Mr. Kutschera is using them for.

iii. One device, called the Camino, uses multiple sensors to detect the walker's gait and changes in gait. It can also detect changes in terrain to help prevent falls in patients. Although this device has many good features, it does way more than Mr. Kutschera needs and is way too expensive. It also does not track the pressure the patient applies to the walker. [1]

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Appendix II: Expense Table

Item	Description	Manufacturer	Mft Pt#	Vendor	Date	QTY	Cost Each	Total
Smart Walker								
N/A								