Abstract

Over 2.2 billion people worldwide are visually impaired, with an estimated 40 million being blind. In the U.S. alone, over 7 million individuals live with some form of visual disability, and that number is expected to grow as the population ages. Many people face daily challenges in navigating indoor environments, such as schools, hospitals, or malls, which often present physical obstacles. Traditional tools like walking canes and guide dogs, while helpful, offer limited sensory feedback and are not always the best suited for crowded environments, nor are they inclusive.

The Hybrid Body suit addresses this critical gap in assistive navigation tools for individuals with visual or mobility impairments. Our solution is a wearable system that combines a haptic vest with a portable vision module, which consists of a camera and can be attached to items such as headbands and glasses. The system has the ability to detect and classify nearby obstacles and gauge depth. This information is transmitted to the user via audio, while the vest communicates directional and proximity cues through vibration patterns around the torso. This setup enables users to independently navigate unfamiliar indoor spaces using tactile feedback.

We prioritized comfort, discretion, and usability by gathering feedback from older community members in St. Louis, Missouri and biomedical professors at Washington University and WashU School of Medicine. Their input helped us improve our design, which delivers intuitive haptic cues as a hands-free alternative. Our prototype has demonstrated success in controlled and random testing, with effective object detection and multi-directional feedback, supporting safer indoor mobility and increased confidence for visually impaired individuals.

Project Objective Statement

Our team designed the Hybrid Body Suit to solve a major limitation in current assistive technology: the lack of truly hands-free, multi-sensory systems for safe and confident indoor navigation. While haptic vests and smart glasses exist independently, no current solution integrates full-body proximity sensing with head-mounted depth vision to deliver real-time, 360-degree spatial feedback purely through tactile cues.

The final wearable system features a lightweight vest embedded with eight time-of-flight depth sensors, each paired with a corresponding vibration motor. These components are distributed strategically around the torso to provide directional obstacle detection and feedback within a half-meter range. The sensors continuously scan the surrounding space, and are processed by an Arduino Portenta H7 microcontroller.

To ensure both comfort and adaptability, the haptic motors and wiring are mounted on an elastic strap system that connects via snap buttons. This dual-strap configuration allows for easy donning and removal, while ensuring that the sensors remain aligned with their intended detection zones. The vest is designed to accommodate various body sizes without compromising sensor placement or signal clarity. Sensor readings are refined with signal processing techniques, including Kalman filters, moving averages, and median filtering, to reduce noise and improve reliability in real-world environments.

A detachable magnetic vision module clips onto standard glasses and runs real-time processing using a Raspberry Pi 4. It combines Roboflow 3.0 for chair detection with Intel's MiDaS for monocular depth estimation. These outputs are fused into a live occupancy grid, allowing the system to identify walkable areas and detect obstacles like chairs without relying on expensive sensors like LiDAR.

The suit uses data from both wearable and visual sensors into continuous, context-aware feedback while staying screen-free, phone-free, and hands-free. Built with feedback from surveying older adults with disabilities and talking with WashU faculty, including Professor Jonathan Hanahan (Human Computer Interaction, Sam Fox) and Dr. Nathan Jacobs (Computer Science, Mckelvey Engineering).

Description of the problem

People with visual impairments often struggle to navigate indoor environments where paths are complex, unfamiliar, or crowded. White canes, the most commonly used tool, only detect objects within arm's reach and provide no information about height, direction, or moving obstacles. Guide dogs, while helpful, are expensive (training can cost over $50,000), require years of wait time, and are not a viable option for many due to allergies, housing restrictions, or ongoing care needs. Finally tools like GPS are largely limited to outdoor environments, and even newer technologies like using ChatGPT with your phone's camera require continuous mobile support, constant hand use, and need stable Wi-Fi, making them impractical in many cases.

This limited access to full environmental awareness results in more falls, slower mobility, and decreased independence, particularly in older adults. For those with early diabetic retinopathy or alzheimer's, the inability to safely interpret physical space can lead to dangerous situations like tripping on uneven surfaces, walking into walls, or missing a step. Such incidents can lead to injuries and premature institutionalization.

The Hybrid Body Suit addresses these gaps by offering a wearable alternative that expands spatial perception through haptic feedback and depth-sensing vision. It alerts users to obstacles at different heights and distances, supports hands-free operation, and doesn't rely on a trained animal or consistent grip like a cane. It also adapts to real-world environments, whether in a crowded room or sitting down .

We are applying for the Rehabilitative and Assistive Technologies and Healthy Aging prizes because our design helps these populations with a scalable and effective solution. By eliminating the high cost and limitations of existing tools, our wearable system makes spatial awareness accessible to people who need it most while retaining a low learning curve and not standing out as off. It promotes independence in aging, and is designed to work in constrained environments where traditional options fall short.

Documentation of the Design

The Hybrid Body Suit is a wearable to improve spatial awareness for the visually impaired and blind in navigating indoor environments. It integrates two sensing platforms: a depth-sensing vision module and a haptic vest worn on the torso that translate visual and spatial data into directional tactile cues.

Mechanical and Hardware Overview

The vest incorporates eight VL53L1X time-of-flight depth sensors, each paired with a vibration motor for location-specific tactile feedback (Fig 1a). The sensors and motors are positioned around the torso to provide 360-degree coverage and detect obstacles within a 0.5-meter range. We also ensured that they are not disrupted by arms being in the way. To resolve I2C (Inter-Integrated Circuit) conflicts between identical sensors, a TCA9548A I2C multiplexer was used, allowing the Portenta microcontroller to poll each sensor.

All components are embedded into an elastic dual snap-button strap system that sits on the main vest. This setup ensures proper alignment of sensors while being inclusive for different body types and retaining directional accuracy. The controller stays in an inner pocket with a small access flap.

The vision module is housed in a CAD (Computer-Aided Design) designed enclosure (Fig. 1b). The module features a magnetic lid and attaches to the right edge of any accessory, such as eyeglass frames. This placement was chosen based on observance that most people are right-handed. Mounting the vision module on the right side ensures a clear front view of the dominant hand.

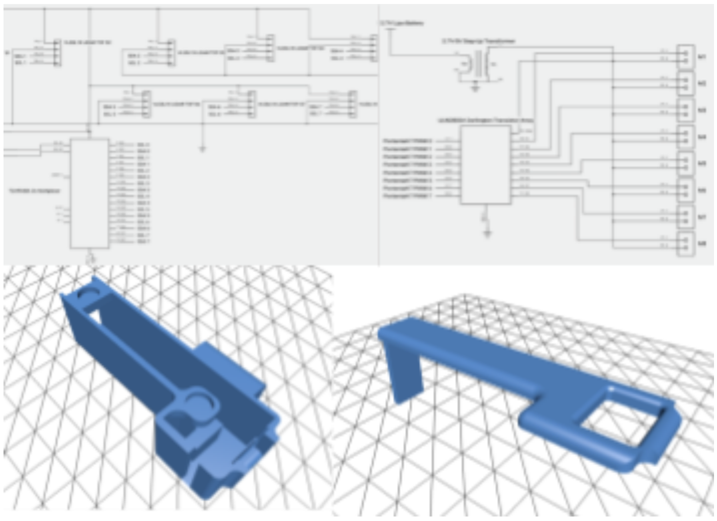


Fig. 1 (a) Breadboard (Haptic/Sensors) and (b) Module

Signal Processing for Vest

The time-of-flight sensors on the vest generate noisy distance data due to reflective surfaces, ambient lighting, and user movement. For intelligent feedback control, we tested multiple models and eventually decided to train XGBoost and Random Forest classifiers (Fig. 2a). To improve signal quality, we implemented the multi-stage filtering pipeline (Fig. 2b) below:

1) Kalman filters to smooth small sensor jitter.
2) Moving averages to reduce step-function noise caused by transient occlusions.
3) Median filters to eliminate outliers.

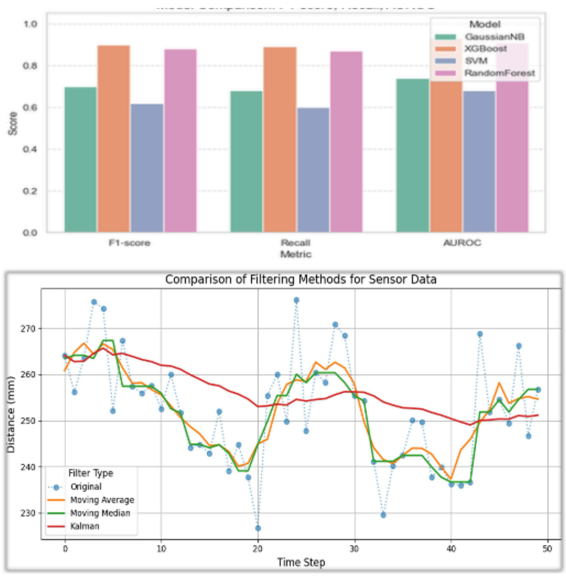


Fig. 2 (a) Model and (b) Filtering Comparison

Object Grid Mapping and Machine Learning for Vision Module

Our detachable vision module clips magnetically onto standard glasses frames and is powered by a Raspberry Pi 4 running a dual-model inference system. Roboflow 3.0 handles chair detection while Intel's MiDaS provides monocular depth estimation. These outputs are fused into a real-time occupancy grid that distinguishes walkable paths from obstacles. Chair detection is overlaid using a custom-trained Roboflow dataset tailored to assist visually impaired users in locating seats indoors.

Depth inference via MiDaS runs on PyTorch, with OpenCV used for efficient image processing. Results are wirelessly transmitted to Bluetooth accessories, enabling immediate user feedback. To stabilize noisy monocular depth data, we apply Exponential Moving Average filtering. Depth estimation runs on alternate frames (frame skipping), while object detection remains full-rate, reducing load without losing accuracy. Metric distance conversion is calibrated via linear regression on known reference points. A multi-threaded architecture separates depth processing from object detection and UI, sustaining 20fps from image input to haptic output. For broader spatial awareness, an ESP32 camera captures high-resolution images on demand, transmitting them via WebRTC linked to GPT-4 Vision API. Users can ask contextual questions like "What's in my path?" and receive descriptions of people, text, or layouts. This conversational interface can work independently from the depth estimation and has multi-turn context, offering an experience with spatial and semantic understanding.

Iterations, Simulations and Pre-Deployment Testing

Before arriving at the final design, we considered a shoe-mounted system (Fig. 3a). This version integrated smaller vibratory motors on the lower leg and time of flight sensors in footwear. However, the feedback was inconsistent due to problems with changes in the angle of incidence and varying reflectivity of floor surfaces. Further because the tibia and fibula bones have little surrounding fat compared to our torso, the vibrations were too subtle to differentiate by direction. In our interview with Professor Jonathan Hanahan of Sam Fox, he further emphasized the importance of aligning haptic feedback with users' natural spatial reasoning and body awareness.

To verify our logic and feedback control before assembling the vest, we made a virtual navigation simulation using Python. This simulated a character in a custom 2D environment with obstacle distance mapped to different vibration zones (Fig. 3b). We tested feedback prioritization, corner detection, haptic suppression, and microcontroller logic under expected signal load from all 8 directions.

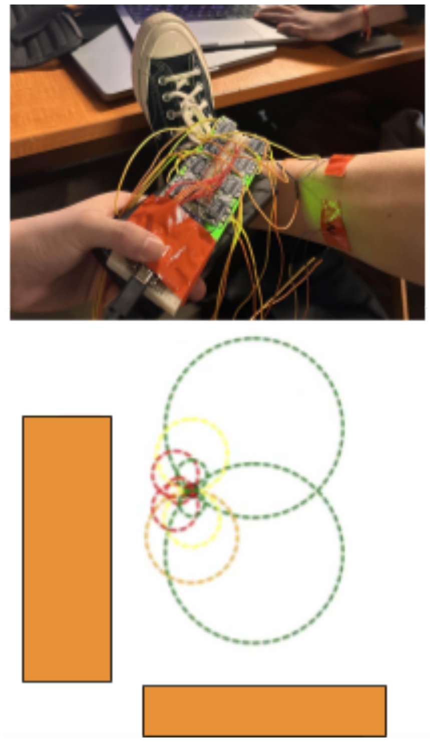


Fig. 3 (a) Initial Prototype and (b) Simulation

Documentation of the Prototype of the Final Design

The Hybrid Body Suit is a lightweight wearable system designed to help people with visual impairments and blindness better understand their surroundings. The suit is made to be easy to wear and fit naturally with everyday clothing and accessories. The prototype focuses on helping users move around safely and confidently.

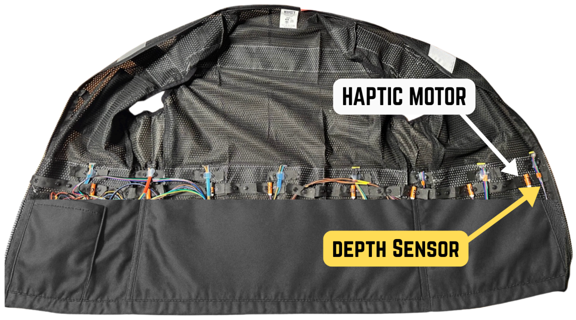
Suit Components

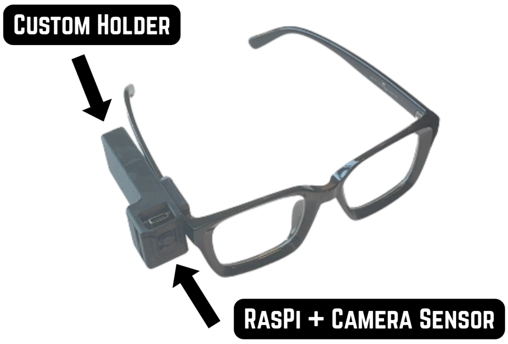
The final Hybrid Body Suit (Fig. 1) is made of two components: a wearable haptic vest that goes around the torso and a detachable vision module that can be mounted onto any eyeglass frames, headband, or existing vision aid. In our testing we opted for non-prescription eyeglasses. This suit was debugged and evaluated through both simulated and real-world testing.

Fig. 1 Student Wearing Hybrid Body Suit

The **haptic vest** is composed of eight time-of-flight depth sensors, each linked to a vibration motor and distributed around the torso for directional tactile feedback. These components are housed within an elastic, snap-button strap system.

The **vision module**, which consists of a camera housed in a custom magnetic housing, runs object detection and depth estimation in real time. The holder has a magnetic lid and easily slides onto any horizontal bar or flat edge, like a glasses arm or head gear. It is also designed to stay upright and balanced to ensure clear camera readings when walking.





Proof of Concept Testing

To evaluate the Hybrid Body Suit in realistic conditions, we conducted informal but focused user testing. Team members wore the suit in both familiar and unfamiliar indoor settings, such as hallways, doorways, and cluttered rooms, while keeping their eyes closed to simulate low-vision scenarios. We made sure to approach this process with respect for people who actually live with visual impairments. To test the haptic vest, we placed obstacles at different heights and angles to see how well the feedback system communicated spatial information. For the vision module, we checked comfort and stability by attaching it to accessories like eyeglass frames and headbands during regular movement, including walking, sitting, and turning. We also tested the depth-sensing feature in two ways: first, while navigating with the module clipped onto a pair of glasses, and second, using a custom GUI that mimicked the exact same code running on a laptop through a webcam. We did this for a showcase event in April (Fig. 2a) where students and parents were able to try it out, along with the vest, and visualize how objects and depth were detected with a color mapping scheme.

These tests showed that the suit offered intuitive and helpful guidance. Field testing was mainly conducted in indoor environments across WashU (Fig. 2b), including hallways and common spaces with objects like walls and chairs. We also received qualitative feedback from older adults similar to those who participated in early pilot surveys. Many valued the hands-free design and ease of use.

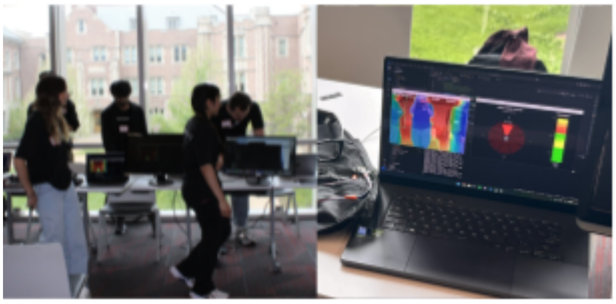


Fig 2a. Software Visualization at Showcase (4/27)   Fig 2b. Suit working at Danforth Campus (Labeled)

Comparison to Existing Solutions

Compared to white canes and guide dogs, the Hybrid Body Suit offers broader spatial awareness and hands-free operation. Canes are limited to ground-level detection and require physical sweeping, while guide dogs are expensive and require long-term care. Commercial systems or just using a camera focuses only on front-facing vision or smartphone integration, which is not apt for someone with vision loss. Our prototype stands out with dual sensory input, tactile feedback, depth mapping, and classification. Additionally, future software updates, such as saving floor layouts, are doable without the need to replace the physical vest.

Video of Hybrid Body Suit and Details

https://youtu.be/Fi5eCiutBAM

Results of a Patent Search and/or Search for Prior Art, Assessment and Patentability

We conducted a patent and prior art search using the USPTO database, academic literature, MIT News, and resources from our institution's technology transfer office. Our goal was to evaluate existing assistive navigation technologies and assess how the Hybrid Body Suit compares in terms of innovation and potential patentability as a hands-free, real-time indoor navigation system for the visually impaired.

Prior Art and Existing Solutions

Several systems have sought to improve navigation for people with visual impairments in indoor environments:

- MIT's Haptic Belt System (2017) uses a 3D camera, vibrational belt, and Braille interface to help users detect surfaces and objects. While it introduced multi-sensory feedback, it does not include real-time occupancy mapping or a modular vision component.
- VTT Wearable Radar Device detects nearby obstacles under clothing using radar and provides vibration feedback, but lacks computer vision, depth estimation, and semantic recognition.
- Path Force Feedback Belt processes environmental features with dual cameras and delivers vibration cues, but has limited detection range and complex feedback interpretation that may reduce usability.
- SUGAR Indoor UWB System uses ultra-wide band sensors and smartphone audio guidance, requiring fixed infrastructure and offering no tactile feedback.
- Smartphone-based tools and AR/VR glasses provide object recognition and audio prompts but typically require screen interaction or internet access, and are not optimized for hands-free or indoor use.

Our Design's Novelty and Patentability

The Hybrid Body suit integrates:

- A modular vision system mounted on glasses, using Roboflow-trained object detection and MiDaS monocular depth estimation
- A haptic vest with eight VL53L1X time-of-flight sensors, each paired with a vibration motor
- Real-time occupancy grid mapping and multi-threaded processing for efficient and responsive performance
- An ESP32-based camera linked to the GPT-4 Vision API, enabling semantic scene descriptions and user-driven questions

This combination provides a screen-free, phone-free, and hands-free user experience that delivers both physical spatial cues and semantic feedback. While individual elements of our system have appeared in prior art, we did not find a wearable device that merges all these components. We believe this integrated approach represents a meaningful variation and could support a novel utility patent, particularly if framed around our system architecture and sensory fusion method.

Marketplace and Future Alternatives

Current alternatives include white canes, guide dogs, and wearable technologies like Aira, OrCam, and .lumen. These serve different needs but may be limited by cost, availability, training requirements, or reliance on residual vision. Our approach aims to complement these tools by offering a modular, intuitive, and accessible system, that goes beyond just a camera with audio cues, shaped by feedback from users and clinical advisors.

Anticipated Regulatory Pathway

Based on FDA guidelines and similar devices, the Hybrid Body Suit would likely be considered a Class II medical device and go through the 510(k) clearance process. It's meant to help people with visual impairments, mobility challenges, or age-related decline navigate indoor spaces more safely. By combining haptic feedback and depth sensing, it improves spatial awareness and reduces fall risk. While it's not therapeutic or diagnostic, it does affect how the body functions, helping users move more confidently, which qualifies it as a medical device under FDA rules.

The Hybrid Body Suit is a non-invasive, non-implantable, and externally worn device with low associated risk. Its most comparable FDA-cleared precedents include:

- BrainPort V100, a sensory device for vision impairment that uses tactile feedback on tongue
- Vibratory sensory aids for balance and posture correction (like Soterix Medical devices)
- Fall-detection wearables that use similar sensor-based feedback mechanisms

Each of these devices received 510(k) clearance. Like these systems, the Hybrid Body Suit uses real-time environmental sensing to provide directional cues via vibrations, but does not introduce new safety concerns.

Due to its function, the system is most likely to fall under one of two classification categories:

- 21 CFR Part 890 (Physical Medicine Devices): This part includes products such as physical performance monitors and mobility aids. If the Hybrid Body Suit is labeled as a device to improve physical navigation or fall prevention, it would be classified here.
- 21 CFR Part 882 (Neurological Devices): This category includes sensory substitution devices and tactile alerting systems. If the system is instead seen primarily as a spatial perception aid for visually impaired users, it could be reviewed under this part. Though this is less likely since there is no direct impact on the nerves, spine, or brain.

Importantly, the Hybrid Body Suit does not deliver electrical stimulation to internal organs, does not interface with neural tissue, and does not alter bodily functions through energy transfer. As such, it is unlikely to require Premarket Approval (PMA), which is typically reserved for Class III. The best pathway we think is therefore expected to be 510(k) clearance.

Reimbursement

We believe the Hybrid Body Suit has a strong chance of being reimbursed by Medicare, Medicaid, or private insurance, especially for people with visual impairments. While it does not have its own billing code yet, similar devices like white canes, sensory substitution tools, and fall-prevention wearables have been covered in the past when prescribed by a doctor or therapist. These items are often reimbursed as durable medical equipment when they help a patient stay safe, move around independently, or avoid injury.

Our device helps with orientation, balance, and indoor navigation. It does not treat a disease, but it improves physical function and reduces fall risk. That is important because falls are a major source of injury and medical costs for older adults and people with low vision. We expect that the device could be billed under a general durable medical equipment code like HCPCS E1399. Although the vision module is also a part of the system, it functions as an input and not a therapeutic device on its own. Hence, we do not expect it to qualify for vision related codes. Instead, the complete suit would be submitted as one assistive device under E1399.

We have also spoken with a doctor who said, "This device's ability to enhance spatial awareness through non-visual cues could even help reduce fall risk in homes, making it a valuable tool for rehabilitation and aging-in-place programs." If shown to improve mobility in more trials, the device could qualify for coverage as part of an aging-in-place plan. As we gather more feedback, we plan to partner with local clinics, including the physical therapy program at WashU, and assistive technology programs to build a case for formal coverage. We also expect that state-level assistive tech programs could help make the device more accessible.

Estimated Manufacturing Costs

Item	Quantity	Unit Cost	Total Cost
TCA9548A I2C Multiplexer	2	6.95	13.9
Seeed Studio XIAO ESP32S3 Camera	1	13.99	13.99
Teyleten Robot TOF400C VL53L1X 4M	8	15.88	127.04
Arduino Portenta H7 Lite Connected	1	106.8	106.8
Safety Vest Black	1	14.99	14.99
ULN2803A Darlington transistor arrays	1	6.99	6.99
6 Pcs DC Coreless Vibration Motors	2	9.99	19.98
Heavy Duty Nylon Canvas Black	2	12.60	24.20
2 Yards Plastic Snaps	1	6.99	6.99
Super Glue Liquid, 2 Pack	1	2.68	2.68
Breadboard Jumper Wires Kit	1	7.99	7.99
24 AWG Flexible Silicone Wire, 30ft	1	15.39	15.39
Solderable PCB Breadboard	1	9.49	9.49
3.7V Lipo Battery 1000mAh (2 pack)	2	9.89	19.78
MT3608 Boost Converter (Pack of 5)	1	5.95	5.95
100ft 22AWG 4pin RGB Wire	1	13.99	13.99
900 Pcs Heat Shrink Tubing Kit	1	6.59	6.59
Clear Lens Glasses Frame	1	9.99	9.99
USB-C Lithium Battery Charger (10 pack)	1	7.99	7.99
Raspberry Pi 4 Model B	1	58.99	58.99
Small Rare Earth Neodymium Magnets 60 Pcs	1	6.98	6.98

Quality assurance cost (30-45 mins @ $20/hr = $15), Assembly labor (2 hrs @ $15/hr = $30)

Total Cost	$545.06

Note: Some components, such as wires, magnets, and heat shrink tubing were purchased in bulk quantities that exceed the amount needed for a single unit. While these materials can be used across multiple prototypes, we have included the full cost of each item to give a conservative estimate.

In mass production, QA might be cheaper due to automation or process standardization, but for low-volume build like now, it’s a manual step, hence the higher time and cost estimate.

Potential Market and Impact

The Hybrid Body Suit is designed to meet a real and growing need: helping people with visual or physical impairments navigate everyday spaces more safely and confidently. It is especially valuable for those who struggle to detect obstacles in indoor environments where white canes and guide dogs fall short. These include crowded classrooms, narrow hallways, shared housing, and unfamiliar clinical or transit facilities. Our solution fills that gap by offering a hands-free, screen-free wearable that gives real-time directional feedback using haptics and vision-based sensing.

Two primary groups stand to benefit from this device: (1) individuals with low vision or blindness, and (2) older adults or rehabilitation patients experiencing spatial disorientation. In the United States, approximately 12 million people aged 40 and older have vision impairment (best visual acuity worse than 20/40), and about 1.1 million are legally blind (USCCR, n.d.). Over 38 million adults aged 70+ face a heightened risk of falls, and vision impairment significantly increases this risk by up to 50% for recurrent falls. Globally, the World Health Organization estimates that 2.2 billion people have vision impairment in 2025, with at least 1 billion cases preventable or treatable, including about 40 million who are blind. As populations age, these numbers are projected to rise, with an estimated 703 million people potentially blind or moderately to severely visually impaired by 2050, driven by conditions like cataracts (Ackland, Resnikoff, & Bourne, 2018).

We estimate that the initial market for the Hybrid Body Suit lies at the intersection of assistive technology, aging-in-place products, and rehabilitation. This includes:

- Individuals with blindness or degenerative eye conditions like retinitis pigmentosa or glaucoma
- Veterans or trauma patients undergoing spatial rehabilitation after injury or trauma
- Older adults looking to maintain independence but facing increased fall risk alone at home
- People with mild cognitive impairment who struggle with general indoor mobility, especially depth

The people using this device might live alone, attend school or college, move around their home, or try to remain independent while aging. They want tools that help them feel safe but don't draw unwanted attention or require complicated training. During surveys with older adults through our "When I'm 64" class, we saw clearly that people wanted something discreet, intuitive, easy to wear and store, not something bulky or robotic.

Our go-to-market strategy focuses on working directly with:

- Occupational therapy and vision clinics
- Veterans Affairs hospitals
- School accessibility programs
- Direct-to-consumer sales online for families and caregivers
- State agencies like Departments of Rehabilitation

We expect the initial cost per unit to be around $500-$700 at low volumes. This reflects our actual component, assembly, and testing costs. With scaled manufacturing, bulk ordering, and simplified production, we believe the unit cost could be reduced to around $250–$300. We've already seen opportunities for volume discounts on electronics and fabric components as explained with our estimated manufacturing costs.

Clinically, we believe this device can reduce falls, increase walking confidence, and reduce caregiver stress. Socially, it can help users move more freely, participate in school or work, and avoid the embarrassment or exhaustion of relying on others. Such emotional independence is difficult to measure but incredibly valuable.

June 10, 2025

To Whom It May Concern,

I'm writing to provide my full support for the Hybrid Body Suit project submitted by the student team consisting of Gaurish Agrawal, Jacqueline Chuang, Leon Zhao, Max Saltrelli, Cadi Zhang, Sonia Palamand, and Lydia Mazeeva for the VentureWell and NIBIB Debut Challenge.

This project was entirely conceived, designed, and implemented by the student team. My role as Faculty Sponsor and advisor to the WashU Robotics Club was limited to providing general guidance and feedback on design, construction, and testing when requested. The students independently developed all components of the Hybrid Body Suit, including the haptic feedback vest**,** computer vision-based module**,** and the object detection and feedback system. While this project is conceptually related to broader assistive technology efforts at Washington University in St. Louis, the work submitted for this competition was completed exclusively by the student team and is distinct from ongoing research projects.

I can also confirm that all team members were enrolled full-time as undergraduates at Washington University in Saint Louis during both semesters of this past academic year. The university does have a Biomedical Engineering Division inside the McKelvey School of Engineering, and I hereby confirm that at least one of the students, Jacqueline Chuang, is enrolled as a full time student in Biomedical Engineering.

Please feel free to reach out if you have any questions.

Sincerely,

Kantaros

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