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Development and Technical Feasibility Evaluation of VertoTrack: An IoT-Based Wearable Head-Orientation Tracker for Rehabilitation Monitoring

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Abstract— Objective motion monitoring is frequently absent from unsupervised home-based vestibular and balance rehabilitation programs, which makes it challenging for patients to adhere to recommended movement boundaries and for clinicians to assess performance. This research introduces VertoTrack, a low-cost wearable Internet of Medical Things (IoMT) prototype that can provide threshold-based aural alarms and quantify angular head displacement in real-time. The system combines an ESP32 microcontroller on a headband with an MPU6050 inertial measurement unit (IMU) to provide pitch and roll data via Wi-Fi to a Blynk mobile dashboard. Using 60 paired pitch and 60 paired roll measurements compared to a digital inclinometer application, sensor performance was verified under three movement circumstances (safe: $<15^\circ$, warning: $15^\circ - 25^\circ$, danger: $\geq 25^\circ$). In every testing zone, Mean Absolute Errors (MAE) stayed below 0.90° . Both roll ($r = 0.9987$, $p < 0.001$) and pitch ($r = 0.9995$, $p < 0.001$) showed strong linear agreement. There was little systematic bias, according to Bland-Altman analysis (roll: -0.07° , 95% Pitch: 0.26° , 95%; LoA: -2.10° to 1.97° LoA: -1.06° to 1.58°). During benchtop testing, the threshold classification system produced two-tier buzzer alerts with 100% accuracy. These results confirm the technical feasibility of VertoTrack for objective head-orientation monitoring during controlled exercise routines.

Keywords—vestibular rehabilitation; head orientation; wearable sensors; threshold-based feedback; mobile health.

I. INTRODUCTION

Continuous brain integration of sensory inputs from the vestibular system, the visual pathway, and peripheral somatosensory receptors is necessary for human postural stability and dynamic balance control. The vestibular labyrinth, located inside the inner ear, has two otolith organs (the utricle and saccule) that detect linear acceleration and gravitational pull, as well as three fluid-filled semicircular canals that detect

rotational head acceleration. These peripheral organs produce accurate, symmetrical signals under normal physiological conditions, which are then sent to the central vestibular nuclei in the brainstem via the vestibulocochlear nerve. The Vestibulo-Ocular Reflex (VOR), which stabilizes visual gaze during head motion, and the Vestibulospinal Reflex (VSR), which preserves postural tone, are two essential compensating reflexes that are driven by this sensory processing [1, 2].

Pathological disruption of this sensory network—resulting from peripheral etiologies such as Benign Paroxysmal Positional Vertigo (BPPV), vestibular neuritis, labyrinthitis, and Meniere's disease, or central deficits following traumatic brain injury and stroke—causes profound sensory mismatch [3]. Rotational vertigo, oscillopsia (apparent movement of stationary visual targets during head motion), chronic dizziness, and postural instability are among the crippling symptoms that patients experience [4]. Affected people consequently drastically limit their everyday head movements, which results in secondary cervical spine stiffness, physical deconditioning, increased fall risks, and notable reductions in health-related quality of life [5].

Vestibular Rehabilitation Therapy (VRT) is an evidence-based, specialized physical therapy intervention designed to promote central nervous system compensation for vestibular deficits [6]. VRT exercises utilize specific movement protocols categorized into three neuroplastic mechanisms: adaptation, substitution, and habituation. Adaptation protocols focus on recalibrating VOR gain through gaze stabilization exercises (e.g., VOR x1 and VOR x2 trainings), requiring patients to perform controlled vertical (pitch) and horizontal/lateral (roll) head oscillations while maintaining visual fixation on a stationary or moving target. While habituation exercises employ repeated exposure to cause moderate, controlled vertigo, which gradually reduces central sensitivity, substitution protocols promote alternate sensory cues (such as visual or somatosensory inputs) to replace decreased vestibular function [7].

Precise motion execution is critical to VRT's therapeutic effectiveness. Head movements must attain particular target angular amplitudes at suitable oscillation frequencies in order to successfully trigger neuronal plastic remodeling. The stimulus does not reach the threshold needed for VOR adaptation if the movement amplitude stays too small. On the other hand, significant motion intolerance, nausea, vomiting, loss of balance, or cervical spine injury might result from extreme head tilt that exceeds recommended safe limits [8].

Physical therapists closely monitor clinical rehabilitation sessions, but the long-term effectiveness of VRT depends on patients completing autonomous home exercise programs (HEPs) twice or three times a day for several weeks. However, there are significant clinical bottlenecks when VRT is moved from supervised clinical settings to unsupervised home settings. Patients find it difficult to appropriately assess their dynamic head orientation angles in the absence of objective feedback devices or professional supervision. According to studies, patients frequently misjudge head inclination by as much as 10.0° to 15.0°, which might result in dangerous overexertion or prudent undertraining [9, 10].

Inaccurate self-reporting and inadequate exercise adherence are further problems with unsupervised home rehabilitation. Currently, during recurring follow-up visits, treating physicians rely on subjective questionnaires or retrospective patient logbooks. Because these subjective instruments lack quantitative kinematic measures, therapists are unable to objectively measure healing trajectories over time, identify compensatory movement faults, or confirm if exercises were performed at therapeutic angles. As a result, there is a pressing clinical need for portable, objective tracking devices that can provide real-time guidance for at-home workouts.

In the past, motion capture methods confined to laboratories have been the mainstay of objective human movement analysis. Passive reflecting markers are used by multi-camera optoelectronic tracking arrays (like Qualisys and Vicon) to measure 3D body segment kinematics with sub-millimeter accuracy. In a similar vein, video-oculography (VOG) goggles, force plates, and electromagnetic tracking devices offer extremely precise diagnostic information [4]. However, these clinical gold standards are limited by the need for skilled clinical operator staff, complicated calibration methods, line-of-sight occlusion constraints, and exorbitant capital costs (sometimes surpassing tens of thousands of dollars). Due of these reasons, advanced motion capture is only available in research labs and tertiary medical facilities [11].

Over the past decade, advancements in Micro-Electro-Mechanical Systems (MEMS) technology have enabled the miniaturization of Inertial Measurement Units (IMUs). Combining 3-axis MEMS accelerometers and 3-axis MEMS gyroscopes onto single semiconductor dies, modern IMUs capture linear acceleration and angular velocity at high sampling rates. When paired with sensor fusion algorithms, wearable IMUs offer a low-cost, lightweight, and unobtrusive alternative for ambulatory motion tracking [12]. Wearable sensor systems eliminate spatial line-of-sight requirements, allowing quantitative kinematic data capture directly in home and community environments [5, 13-15].

A revolutionary method of remote mHealth monitoring is the incorporation of wearable IMU sensors into the Internet of Medical Things (IoMT) ecosystem. Motion data can be easily sent to cloud platforms and mobile applications by combining wearable microcontrollers (such the low-power ESP32) with wireless telemetry protocols (Wi-Fi, Bluetooth Low Energy). [16]. This cloud-connected telemetry enables real-time exercise visualization for patients alongside asynchronous data logging for clinician review. [3, 17, 18]

Real-time sensory biofeedback is essential for motor relearning in addition to data transfer [19]. Visual (display screens), tactile/haptic (vibration motors), or auditory (acoustic tones) stimuli are common biofeedback methods. Auditory biofeedback has substantial biomechanical advantages over visual biofeedback in the particular setting of vestibular rehabilitation. Requiring patients to watch a mobile smartphone screen divides visual attention, impairs VOR suppression/adaptation mechanics, and causes undesired neck movement because VRT exercises specifically call for visual fixation on fixed gaze targets. Head-mounted auditory alerts deliver hands-free, eye-free orientation feedback, allowing patients to maintain uninterrupted visual focus while receiving instant acoustic confirmation of movement boundaries.

Despite growing interest in wearable rehabilitation devices, existing commercial mHealth platforms are often cost-prohibitive, rely on proprietary closed software architectures, or focus broadly on lower-limb gait and posturography rather than isolated head orientation [20, 21]. There remains a clear technological gap for an open-architecture, low-cost wearable headband capable of tracking dual-axis head inclination (pitch and roll) with high accuracy while delivering automated, multi-tiered acoustic feedback [22].

To address these clinical and technological challenges, this study presents the design, development, and benchtop feasibility evaluation of VertoTrack—a portable IoMT

wearable head-orientation tracking headband. The specific contributions and objectives of this work are threefold:

1. **Hardware & Firmware Integration:** Construct an open-architecture, lightweight wearable device combining an MPU6050 IMU, an ESP32 microcontroller, a rechargeable Li-ion power circuit, and a piezo buzzer into a wearable headband.
2. **Multi-Tier Biofeedback Algorithm:** Implement an automated, two-tier threshold classification algorithm that triggers distinct acoustic warning and danger alerts when angular displacement exceeds clinical safety thresholds.
3. **Experimental Feasibility Validation:** Benchmark VertoTrack tracking accuracy, linear correlation, and statistical limits of agreement against a reference digital inclinometer across safe, warning, and danger movement zones.

II. MATERIALS AND METHODS

Four functional elements make up the VertoTrack hardware architecture: sensor, micro-processing, feedback, and power management. The MPU6050 IMU, which contains a 3-axis MEMS accelerometer and a 3-axis MEMS gyroscope, is the primary sensor component. An ESP32 microcontroller manages wireless data transmission and central processing. A rechargeable lithium-ion battery provides power, which is managed via an SPST rocker switch and a TP4056 charging module with short-circuit protection. Detailed connections are provided in Table 1, and the corresponding circuit diagram is shown in Figure 1. The MPU6050 is positioned flush against

the center of the forehead thanks to the integration of the entire circuit assembly into an adjustable cloth headband.

Table 1. Hardware pin allocation, interface connections, and system functions for the VertoTrack wearable headband assembly.

Component	Component Pin	ESP32 Connection	Function
MPU6050 IMU	VCC	3.3V	Power supply (3.3 V)
	GND	GND	Common ground
	SDA	GPIO21	I ² C Serial Data line
	SCL	GPIO22	I ² C Serial Clock line
Piezo Buzzer	Positive (+)	GPIO25	Digital signal output for alert PWM
	Negative (-)	GND	Common ground
TP4056 Module	OUT+	VIN	Regulated 5V system input & ground distribution
	OUT-	GND	
Power Unit	TP4056 OUT+	VIN	Main board supply voltage (5 V input)
	TP4056 OUT-	GND	System ground

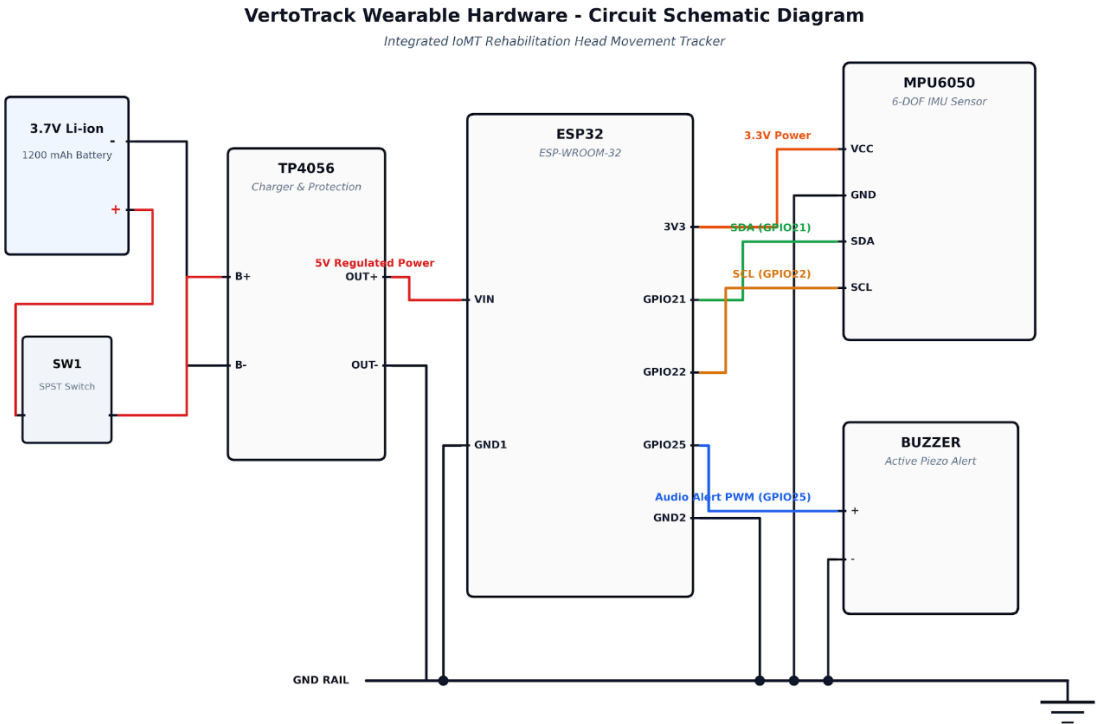


Figure 1. Circuit schematic diagram of the VertoTrack wearable hardware architecture, illustrating pin-to-pin connections between the ESP32 microcontroller, MPU6050 IMU sensor, TP4056 lithium power management unit, 3.7V Li-ion battery.

The microcontroller firmware was programmed using the Arduino IDE environment. The algorithm operates on a 20ms sampling loop (50Hz) to parse accelerometer and gyroscope raw registers. Angular pitch (θ_{pitch} , representing forward flexion and backward extension) and roll (ϕ_{roll} , representing lateral left and right shoulder tilt) are derived from the gravitational vector components:

$$\theta_{\text{pitch}} = \arctan \left(\frac{A_y}{\sqrt{A_x^2 + A_z^2}} \right) \times \frac{180}{\pi}$$

$$\phi_{\text{roll}} = \arctan \left(\frac{-A_x}{A_z} \right) \times \frac{180}{\pi}$$

To eliminate initial sensor placement tilt, an automated 2-second calibration routine executes upon boot, storing baseline offsets (pitchOffset, rollOffset). An exponential smoothing filter (alpha = 0.88) removes dynamic motion noise, while a 2.0° deadzone zeros out static micro-vibrations. Movement categorization evaluates the maximum absolute angle against user-configurable limits, as listed in Table 2.

Table 2. Angular movement threshold categorization matrix, absolute head tilt boundaries, and corresponding two-tier acoustic piezo buzzer alert patterns.

Absolute angle	Buzzer	Condition
$< 15.0^\circ$	Inactive	Safe Zone
$15.0^\circ \leq \text{Angle} < 25.0^\circ$	Slow pulsed tone (700 Hz, 180ms interval).	Warning Zone
$\text{Angle} \geq 25.0^\circ$	Rapid pulsed tone (700 Hz, 120ms interval).	Danger Zone

VertoTrack incorporates the Blynk IoT cloud architecture over Wi-Fi to offer interactive control and remote mHealth tracking, as shown in Figure 2. The BlynkSimpleEsp32.h library uses non-blocking timer callbacks to connect the ESP32 to the Blynk server. Six essential user interface (UI) widgets tied to certain Virtual Pins (V0–V4) make up the bespoke Blynk mobile interface:

- Pitch Angle Gauge Widget (Virtual Pin V0): Shows vertical head displacement in real time with a resolution of 0.1° (-90.0° to $+90.0^\circ$).
- Roll Angle Gauge Widget (Virtual Pin V1): Shows lateral head tilt in real time with a resolution of 0.1° (-90.0° to $+90.0^\circ$).
- Movement Alert Status LED Widget (Virtual Pin V2): This color-coded visual indicator shows red for danger (2), yellow for warning (1), and green for normal (0).
- Warning Threshold Slider Widget (Virtual Pin V3): This interactive slider lets users or medical professionals choose the warning trigger threshold (default: 15.0° , range: 5.0° to 45.0°).
- Danger Threshold Slider Widget (Virtual Pin V4): An interactive slider that lets you change the danger threshold (default: 25.0° , range: 15.0° to 90.0°).
- Head Movement History SuperChart Widget: A time-series graph for clinical session review that plots pitch and roll angles over time (adjustable views: Live, 1h, 6h, 1d, 1wk).

The firmware separates telemetry into three distinct timing loops in order to preserve maximum network efficiency while guaranteeing immediate alert delivery:

- High-Frequency Processing Loop (20 ms/50 Hz): This loop uses the ESP32 to read MPU6050 registers, compute pitch/roll, apply hysteresis, and control piezo buzzer tone patterns locally.
- Blynk Telemetry Stream (3000 ms/0.33 Hz): Sends real-time numerical pitch (V0) and roll (V1) coordinates to the Blynk cloud server for chart plotting and UI gage.
- Alert status changes are tracked by Event-Driven Alert Synchronization (200 ms/5 Hz) (V2). In order to prevent smartphone notification spam, the system instantly refreshes the app LED and initiates Blynk.logEvent() push notifications (such as "warning_alert" or "danger_alert") with a 60-second cooldown buffer (notificationCooldown = 60000 ms).

Additionally, any threshold changes made on the mobile phone are instantly synchronized to ESP32 flash memory via the Preferences thanks to two-way slider synchronization (BLYNK_CONNECTED and BLYNK_WRITE).h library, guaranteeing consistent operating limitations over power cycles of the device.

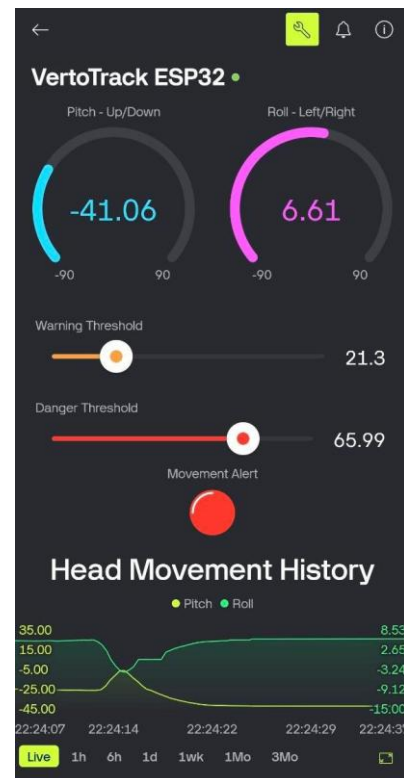


Figure 2. Custom Blynk mHealth mobile application user interface, displaying real-time pitch and roll radial gauge widgets, color-coded movement alert status LED, adjustable threshold slider widgets, and historical time-series trajectory graph (SuperChart).

In a controlled laboratory testing, prototype accuracy was assessed. The comparative reference tool was a mobile application at the digital level called Bubble App. The three movement zones (Safe, Warning, and Danger) were used for testing. The VertoTrack headband with the sensor positioned in the mid-sagittal plane was worn by the subject during each test

trial. The reference device was installed parallel to the headband frame at the same time. Across all positive and negative motion trajectories, 60 paired roll and 60 paired pitch measurements (20 pairs per movement condition) were recorded.

Pitch and roll datasets underwent independent statistical evaluations:

1. Descriptive Metrics: To represent motion dispersion, mean absolute angles ($\bar{X}$) and standard deviations (SD) were computed.
2. Error Calculation: The entire measurement deviation was calculated using Mean Absolute Error (MAE):

$$MAE = \frac{1}{n} \sum_{i=1}^n |Y_{VertoTrack,i} - Y_{Reference,i}|$$

3. Correlation Analysis: To maintain directionality, Pearson's correlation coefficient (r) assessed linear relationship using signed orientation angles.
4. Agreement Analysis: Bland-Altman illustrates the 95% Limits of Agreement (LoA = $d^2 \pm 1.96 \cdot SDd$) and identified systematic measurement bias ($\bar{d}$).

III. RESULTS

Across all test conditions, VertoTrack measurements demonstrated close alignment with reference values. Table 3 summarizes the descriptive statistics and MAE values across the safe, warning, and danger zones.

Table 3. Descriptive angular statistics (Mean $\pm$ SD) and Mean Absolute Error (MAE) metrics across movement zones for roll and pitch tracking (n = 60 paired measurements per axis).

Movement Zone	Axis	VertoTrack Absolute Mean $\pm$ SD ($^{\circ}$)	Reference Absolute Mean $\pm$ SD ($^{\circ}$)	Mean Absolute Error, MAE ($^{\circ}$)
Safe (<15 $^{\circ}$)	Roll	8.32 $\pm$ 3.78	8.50 $\pm$ 3.82	0.70
	Pitch	8.66 $\pm$ 3.28	8.45 $\pm$ 3.25	0.24
Warning (15 $^{\circ}$ –25 $^{\circ}$)	Roll	18.41 $\pm$ 2.42	18.40 $\pm$ 2.23	0.89
	Pitch	18.85 $\pm$ 2.53	18.55 $\pm$ 2.16	0.55
Danger ($\geq$ 25 $^{\circ}$)	Roll	28.30 $\pm$ 2.55	28.55 $\pm$ 2.70	0.76
	Pitch	28.10 $\pm$ 2.71	28.55 $\pm$ 2.70	0.78

The maximum observed MAE across all trials was 0.89 $^{\circ}$ (warning roll zone), while the minimum MAE was 0.24 $^{\circ}$ (safe pitch zone). In all cases, average measurement error remained below 1.0 $^{\circ}$.

Figure 3 illustrates the close agreement between the roll angle measurements made with the VertoTrack wearable headband device and the reference Bubble App under safe, warning, and danger movement scenarios. In a similar vein, under all movement conditions, the pitch angle measurements showed good agreement between the two systems (Figure 4). These results show that, when compared to the reference device, VertoTrack can accurately measure head movement angles with comparatively modest measurement errors.

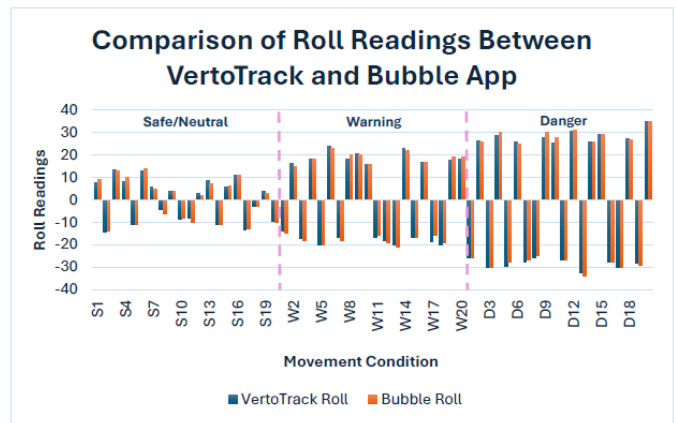


Figure 3. Comparison of roll angle measurements between the VertoTrack wearable headband device and the reference Bubble App across safe, warning, and danger movement conditions.

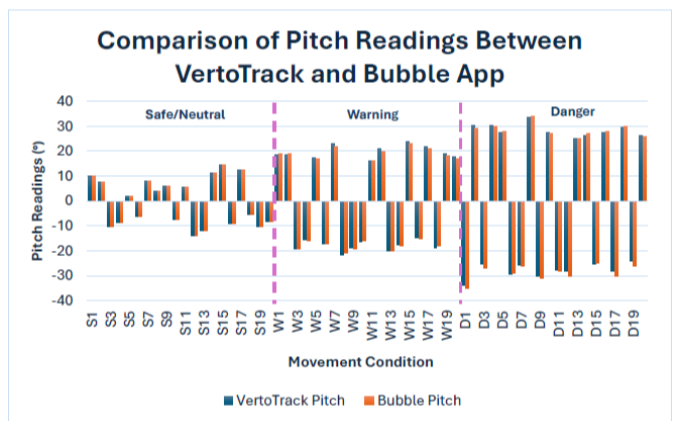


Figure 4. Comparison of pitch angle measurements between the VertoTrack wearable headband device and the reference Bubble App across safe, warning, and danger movement conditions.

Near-perfect linear connections were shown by Pearson correlation analysis for both movement axes (n = 60):

- Roll Axis (Figure 5): regression line $y = 1.0057x + 0.066$ ($R^2 = 0.9975$), $r = 0.9987$, $p < 0.001$.
- Pitch Axis (Figure 6): regression line $y = 1.0032x - 0.2597$ ($R^2 = 0.9989$), $r = 0.9995$, $p < 0.001$.

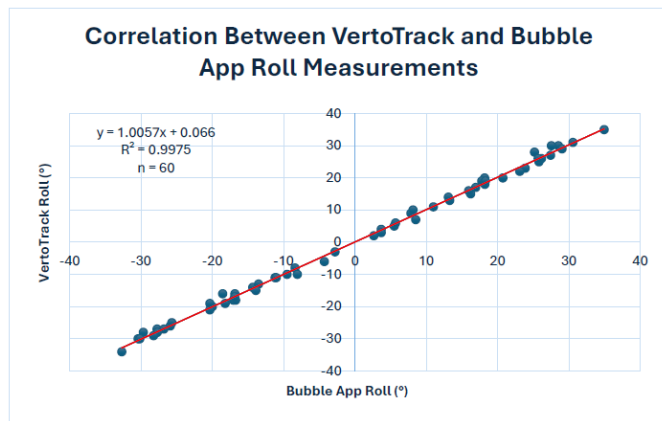


Figure 5. Pearson linear correlation scatter plot for roll angle measurements between VertoTrack and the reference Bubble App, demonstrating strong linear agreement.

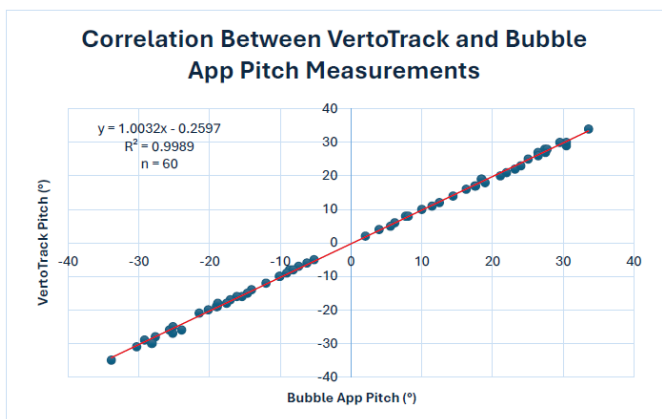


Figure 6. Pearson linear correlation scatter plot for pitch angle measurements between VertoTrack and the reference Bubble App, demonstrating strong linear agreement.

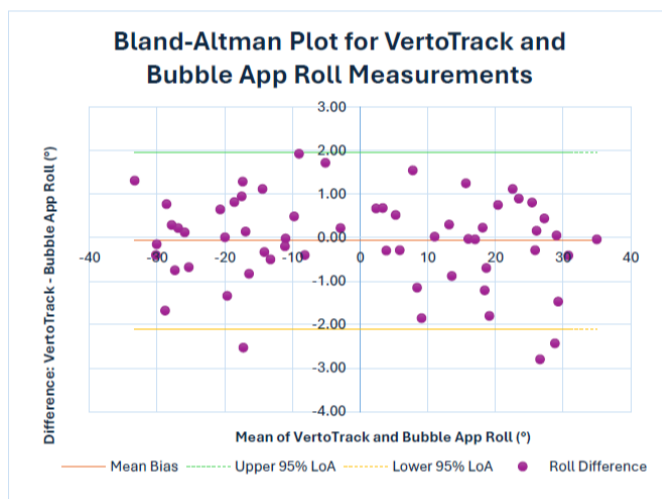


Figure 7. Bland–Altman agreement plot for roll angle measurements between VertoTrack and the reference Bubble App, showing a mean bias of -0.07° with 95% Limits of Agreement (LoA) ranging from -2.10° to 1.97° (95.0% of data points within LoA).

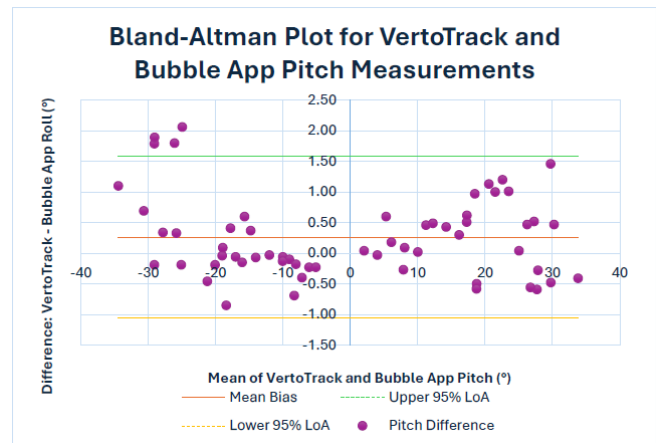


Figure 8. Bland–Altman agreement plot for pitch angle measurements between VertoTrack and the reference Bubble App, showing a mean bias of -0.26° with 95% Limits of Agreement (LoA) ranging from -1.06° to 1.58° (93.3% of data points within LoA).

Minimal systematic discrepancy was confirmed by Bland–Altman agreement plots:

- Roll Angle (Figure 7): The average bias ($\bar{d}$) was -0.07° (SDd = 1.04°). 57 out of 60 paired measurements (95.0%) fell within the 95% Limits of Agreement, which varied from -2.10° to 1.97° .
- Pitch Angle (Figure 8): The mean bias ($\bar{d}$) was 0.26° (SDd = 0.67°). 56 out of 60 paired measurements (93.3%) fell within the 95% Limits of Agreement, which varied from -1.06° to 1.58° .

Throughout all 60 trials, the firmware classification engine was assessed. Throughout all 20 safe zone trials, the piezo buzzer did not sound (0% false alarm rate). The slow auditory pattern appropriately engaged in all 20 trials within the warning zone (15° – 25°). In all 20 trials, the quick auditory alert worked flawlessly in the danger zone ($\geq 25^\circ$). Under carefully monitored benchtop circumstances, the overall threshold classification accuracy approached 100%.

IV. DISCUSSION

The experimental evaluation confirms that the VertoTrack prototype achieves high angular tracking accuracy during benchtop testing across static and dynamic motion trajectories. Across all three testing conditions, the Mean Absolute Error (MAE) between VertoTrack and the reference mobile inclinometer remained under 0.90° for both axes. Specifically, pitch tracking exhibited exceptionally low mean errors (0.24° in the safe zone, 0.55° in the warning zone, and 0.78° in the danger zone), while roll tracking maintained comparable error bounds (0.70° , 0.89° , and 0.76° , respectively).

Pearson correlation analysis demonstrated near-perfect linear agreement between VertoTrack and reference angle measurements across 60 paired roll ($r = 0.9987$, $p < 0.001$) and 60 paired pitch ($r = 0.9995$, $p < 0.001$) trials. Complementing this, Bland–Altman agreement plots revealed negligible systematic biases of -0.07° for roll (95% Limits of Agreement: -2.10° to 1.97°) and 0.26° for pitch (95% Limits of Agreement: -1.06° to 1.58°). The slightly tighter limits of agreement

observed in pitch measurements suggest greater sensor stability during vertical sagittal plane motion compared to lateral coronal tilting. The microcontroller's low-level register processing and I2C bus design are responsible for this sub-degree tracking accuracy. The system successfully reduces initial zero-offset bias and MEMS accelerometer noise by using non-blocking hardware timers to execute sensor sampling routines at a 20 ms interval (50 Hz execution loop) and by performing initial zero-offset calibration in a neutral posture before exercise sessions.

The Blynk mHealth application's integration of wireless telemetry creates an Internet of Medical Things (IoMT) connection between clinical supervision and at-home workouts. The multi-rate firmware architecture strikes a compromise between wireless cloud telemetry and instantaneous local processing:

1. Local Motion Loop (50Hz): Continually updates local buzzer alerts every 20 milliseconds by computing sensor math.
2. Alert Event Checker (5Hz): When a threshold boundary changes, it sends movement status updates to Blynk Virtual Pin V2 every 200ms.
3. Telemetry Streaming Loop (0.33Hz): This loop maintains cloud stability without using up network bandwidth by sending numerical pitch (V0) and roll (V1) values to the mobile interface every 3000ms.

Clinicians can personalize movement limitations based on each patient's neck range of motion and clinical rehabilitation programs using the interactive slider controls on Virtual Pins V3 (Warning Threshold) and V4 (Danger Threshold). Using the Preferences, custom thresholds are saved straight to the non-volatile flash memory of the ESP32.h library, maintaining configurations during power cycles. Furthermore, during follow-up visits, the time-series SuperChart widget records long-term motion history, providing therapists with an objective record of workout compliance, angular velocity trends, and gains in range of motion.

VertoTrack strikes a compromise between cost, portability, and active feedback when compared to current head-tracking and vestibular rehabilitation devices:

- DizzyFIX: Epley motions for BPPV are guided by a mechanical fluid bead in a transparent tube. Although inexpensive, it necessitates visual monitoring and does not provide digital data logging or electrical sensor tracking.
- Vertigenius: A head-mounted IMU system featuring a clinician web portal and smartphone app. It has more expensive equipment and does not have local acoustic buzzer feedback on the headband itself, despite its strong functionality.
- Otolith Labs (NVRT): An expensive therapeutic headband that uses non-invasive bone-conduction vibration instead of active motion tracking to treat chronic vertigo.
- VertoTrack: Integrates inexpensive MEMS components, non-blocking wireless cloud telemetry, local real-time audio biofeedback, and adjustable threshold boundaries.

Limitations:

A number of methodological and engineering limitations must be recognized in order to guaranty accurate interpretation of the experimental results:

1. Single-Sensor Placement Restrictions: VertoTrack uses a single IMU installed on a headband. This measures head inclination in relation to the gravitational vector (pitch and roll) precisely, but it cannot distinguish between isolated cervical head tilt and whole-body trunk flexion, waist bending, or deliberate lying down. Additionally, the system cannot record 3-axis horizontal head yaw rotation (turning head left or right) without experiencing gyroscopic yaw drift over time due to the MPU6050's lack of a 3-axis magnetometer.
2. Reference Instrument Limitation: Rather than using a 3D optical motion capture array, prototype accuracy was verified using a commercial smartphone inclinometer. Future research must validate against optical motion capture standards, even though it is appropriate for benchtop feasibility testing.
3. Cohort and Clinical Scope: Healthy motion trajectories were tested in a controlled laboratory setting. Clinical cohorts with acute or chronic vestibular disorders were not used to test the prototype.
4. Non-Diagnostic & Non-Fall Detection Boundaries: The gadget is only used for biofeedback and motion tracking. It does not assess postural balance, measure the center of mass of the entire body, identify vestibular disorders, or identify actual falls.

V. CONCLUSIONS

Real-time head-orientation tracking, threshold classification, piezo auditory feedback, and wireless telemetry are all effectively accomplished by the VertoTrack prototype. When compared to reference measurements, benchtop tests show a strong linear correlation ($r > 0.998$) and sub-degree absolute error ($MAE < 0.90^\circ$) across the pitch and roll axes. These results validate VertoTrack's technical viability as a mobile health monitoring tool for regulated rehabilitative programs.

VertoTrack bridges a critical gap in unsupervised home-based rehabilitation. By providing immediate, head-mounted acoustic biofeedback, it informs patients when head tilting exceeds safe exercise limits without requiring visual screen tracking. Simultaneously, the mHealth dashboard equips clinicians with objective quantitative records to evaluate patient compliance and motion trends between scheduled clinic appointments.

NOMENCLATURE

BPPV	Benign Paroxysmal Positional Vertigo	
IoMT	Internet of Medical Things	
LoA	Limits of Agreement	Degree (°)
MAE	Mean Absolute Error	Variable
MEMS	Micro-Electro-Mechanical Systems	
IMU	Inertial Measurement Unit	
N	Total number of observations	Count
SD	Standard Deviation	Variable
r	Pearson linear correlation coefficient	-1 to +1
HEP	Home Exercise Programme	

VOR Vestibular-Ocular Reflex
VRT Vestibular Rehabilitation Therapy

Greek letters

$\bar{d}$ Average bias

θ_{pitch} Calculated angular pitch displacement Degree (°)

ϕ_{roll} Calculated angular roll displacement Degree (°)

CONFLICT OF INTEREST

The authors have no competing interests relevant to this article.

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DECLARATION OF AI-ASSISTED TOOLS USAGE

AI-assisted tools were used solely for language editing to improve grammar, clarity, and readability. An AI-detection assessment reported a score below 15%. The authors have critically reviewed and verified all revisions and accept full responsibility for the accuracy, originality, integrity, and entire content of the manuscript.

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