The Balance Toolkit: Democratizing Balance-Based Interaction Through Open-Source Software for Repurposed Wii Balance Boards

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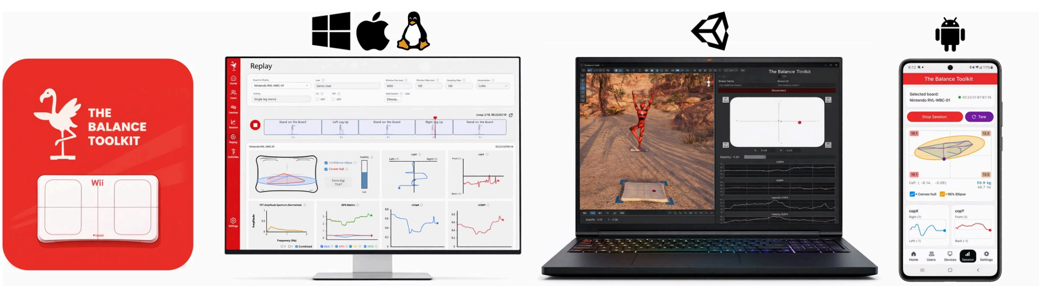

Fig. 1. The Balance Toolkit ecosystem: application logo, desktop posturography dashboard, Unity integration sample, and Android companion application.

Balance-based interaction offers unexplored design space for games, rehabilitation, and accessible play, but remains confined to proprietary platforms. The Wii Balance Board (WBB) is an inexpensive balance board that correlates highly with research-grade equipment (r=0.99). However, existing software prevents developers from exploring balance mechanics due to platform limitations, complex Bluetooth pairing protocols, and a lack of real-time integration. We present The Balance Toolkit, an open-source framework that enables balance-based player-computer interaction using repurposed consumer hardware. Co-designed with experts (N=26), we provide cross-platform connectivity across Windows, macOS, Linux, Android, dual-board support, game engine integration, LSL and TCP integration, and six posturography activity templates. First-use testing with 5 experts achieved mean SUS usability scores of 77.0 (SD=8.2). By democratizing access to 42 million manufactured boards, we enable community innovation at the intersection of play and health.

CCS Concepts: • **Human-centered computing → Systems and tools for interaction design**; **User interface toolkits**.

Additional Key Words and Phrases: Wii Balance Board, Balance-based interaction, Posturography, Exergaming, Open-source software, Windows, macOS, Linux, Android, Unity

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1 Introduction

Balance-based interaction offers rich potential for games, rehabilitation, and accessible play. Weight shifting and postural control enable novel mechanics, from VR locomotion [27, 33, 71] to asymmetric multiplayer experiences [36], while balance-based exergames show clinical promise for fall prevention [38, 47, 69], neurological rehabilitation [41, 62], and physical activity engagement [40]. Moreover, postural control connects to cognitive function [66], emotional state [26, 37], and motor performance [28], making balance a uniquely expressive input modality that reveals both physical and mental state during play. Despite this potential, balance-based interaction remains confined to proprietary platforms like Wii Fit [50] or expensive medical-grade hardware, limiting broader exploration by the games research and development community.

A key barrier is infrastructure. Traditional posturography equipment costs $10,000–$100,000 USD, requires dedicated laboratory space, and demands specialized expertise [11]. The Nintendo Wii Balance Board (WBB) offers a validated low-cost alternative, with high correlations ($r = 0.99$) to laboratory-grade force plates [13, 29], and over 42 million units have been manufactured. Yet this hardware opportunity remains largely unrealised. Existing WBB software solutions are platform-specific, abandoned or closed-source, encumbered by restrictive licenses, or lack real-time game engine integration. Without shared infrastructure, each research group must reinvent basic device connectivity from scratch, preventing ecosystem formation around an otherwise ideal device.

To address this gap, we present **the Balance Toolkit**, a fully open-source framework that democratizes balance-based interaction through repurposed consumer hardware. We grounded the toolkit design in a co-design process with 26 domain experts spanning posturography research, rehabilitation, and game development, following established HCI toolkit methodology [35] to ensure requirements reflect real community needs. The resulting toolkit comprises a cross-platform desktop application (Windows, macOS, Linux), ready-to-use Unity and Python integration samples, and an Android companion application for real-time data collection and visualization, all designed with an explicit focus on long-term sustainability and community contribution.

Technical evaluation indicates sub-0.5 ms core processing latency across all supported platforms, suitable for responsive balance-based gameplay. A first-use study with five domain specialists showed that all participants completed every workflow without assistance, rating overall usability as good and acceptable (SUS $M = 77.0$, $SD = 8.2$, 73rd percentile). The hardware opportunity has existed for over a decade. The Balance Toolkit resolves the infrastructure barrier that has prevented it from being realised.

The main contributions of this work are

(1) the design and implementation of **the Balance Toolkit**, an open-source framework for balance-based interaction that unifies device connectivity, real-time streaming, visualization, and challenge templates, grounded through co-design with 26 domain experts,
(2) characterization of connection behavior and processing latency across operating systems,
(3) a first-use evaluation of the desktop application with domain specialists examining workflow completion and perceived usability.

2 Related Work

We review balance-based interaction applications, existing WBB software solutions, and the infrastructure gaps that motivated our toolkit development.

2.1 Balance-Based Interaction: From Gaming to Clinical Assessment

Balance-based interaction spans entertainment, rehabilitation, and clinical research. Nintendo's Wii Fit [59] popularized balance gaming, demonstrating consumer appetite for weight-shifting mechanics and postural challenges, but its closed ecosystem prevented developers from accessing raw sensor data or exploring novel game mechanics. Subsequent commercial exergaming platforms have shown effectiveness for fall prevention [2, 12], neurological rehabilitation [57], and physical activity engagement [31], yet remain similarly proprietary.

Alternative game input devices offer instructive comparisons. Microsoft Kinect enabled full-body motion capture [6] but lacked force measurement precision for balance assessment. Ring Fit Adventure demonstrated continued fitness gaming interest [51] but maintained closed integration. Dance pads and motion controllers provide spatial input [43] but cannot measure center of pressure or weight distribution. These devices illustrate the consumer accessibility versus measurement precision trade-off that the Wii Balance Board partially addresses by combining low-cost consumer availability with access to force-derived balance measures.

Balance has also been explored as a compelling input modality for games and playful interactive systems because it turns posture, leaning, and weight shifting into continuous embodied control. Prior work has used the WBB's pressure sensors for continuous and discrete VR input, including navigation, rotation, mode switching, and object manipulation [15]. Williams et al. [73] further showed that WBB-derived centroid position and rate of change can support walking-in-place locomotion in virtual environments, suggesting that balance signals can provide more embodied navigation than joystick input. In active-game contexts, Brehmer et al. [8] abstracted WBB input as "stance" for steering and acceleration, while Kerber et al. [32] used directional weight shifts to control movement in a first-person shooter. Work with children also shows that balance-based play can support engagement, competition, and embodied learning, from WBB-controlled maze navigation in DoodleMaze [44, 45] to balance-centered learning systems such as BalanSAR and Balance Board Math [42, 64]. These systems show that balance is not only a rehabilitation or assessment signal. Center of pressure, weight distribution, directional leaning, rocking amplitude, and movement timing can all become meaningful game inputs. However, these mappings are typically implemented inside one-off prototypes, leaving developers without reusable tools for accessing, visualizing, and remapping balance signals across games and interactive applications.

These interaction examples motivate the WBB as a game input device, while clinical validation work explains why the same low-cost hardware can also support quantitative balance sensing. In clinical and research contexts, the WBB has undergone extensive validation. Studies demonstrate high correlations ($r = 0.99$) with laboratory-grade force plates for center of pressure measurements [29]. Park et al. [54] found strong device correlation (ICC = 0.77–0.89) and test-retest reliability (ICC = 0.81–0.91). Leach et al. [34] demonstrated that the WBB can achieve measurement errors as low as 0.5–2mm, establishing research-grade precision. This validation establishes the WBB as viable infrastructure for both posturography and interactive applications, yet software limitations have prevented realizing this potential.

2.2 Existing WBB Software Solutions

While the WBB hardware has been validated across clinical and research contexts, existing software solutions remain fragmented across platforms, abandoned by developers, or locked behind proprietary systems. We organize these limitations into three categories.

Platform-specific tools. achieve technical quality within constrained environments but limit broader adoption. RombergLab [58] (macOS-only, inactive since 2016) provided direct Bluetooth connectivity with strong clinical validation (ICC = 0.94), but its platform restriction excluded Windows-dominant research labs and its clinical focus prevented use in interactive applications. BrainBLOX [14] (Windows-only, abandoned in 2014) offered real-time visualization and raw sensor access but exemplified the sustainability challenges of platform-locked academic tools. Wii Balance Board Recorder [68] provides Windows-based functionality with strong documentation and data export, but offers only connection protocols and raw data access without processing pipelines. These projects prove that effective WBB software is feasible, but platform dependencies undermine long-term viability and cross-institutional adoption.

Web-based platforms. pursued cross-platform access but introduced infrastructure fragility. SeeSway [13] delivered advanced analysis including wavelet transforms and sample entropy calculations, extending research beyond traditional metrics. However, its reliance on centralized servers created a single point of failure: when server maintenance ceased, the platform became inaccessible, obsoleting dependent research workflows. This highlights risks inherent to server-dependent architectures, including data privacy concerns, lack of offline access in clinical or low-connectivity settings, and threats to research continuity. The WBB Posturography R Shiny Application [70] addressed some of these concerns as an open-source, browser-based tool requiring no installation, designed for both research and clinical workflows. However, it still lacks real-time integration capabilities essential for interactive or biofeedback-driven applications.

Commercial solutions. provide professional support and reliability at the cost of accessibility and extensibility. The Wii Balance Board Extension for LabChart [1] integrates with established data acquisition platforms, offering reliable real-time streaming and comprehensive analysis tools backing numerous published studies. However, expensive proprietary licensing restricts access for educational institutions and resource-limited contexts, while closed-source implementation prevents customization or integration with game engines and biofeedback systems. The extension also provides no real-time API for external application integration.

2.3 HCI Infrastructure and Toolkit Contributions

Infrastructure research occupies a distinctive and often undervalued position within HCI [18]. The history of successful HCI toolkits reflects a recurring pattern where reducing authoring complexity and creating paths of least resistance enables new audiences to engage with previously inaccessible interaction modalities [21, 48], from Phidgets making sensor-based interfaces accessible to software developers [22] to d.tools lowering the barrier for physical prototyping [24]. Tanenbaum et al. [65] establish democratization as a recognized HCI concept, describing how accessible tooling enables new audiences to move from consumption to active creation. Hodges [25] extends this to hardware specifically, arguing that while prototyping has been democratized, the transition to sustainable and reproducible infrastructure remains the critical unsolved challenge. We use the term in this precise sense: the WBB hardware barrier has long been resolved, but the lack of maintainable software infrastructure has kept balance-based interaction inaccessible to developers and researchers without posturography expertise, with existing tools emerging from narrow research contexts with limited documentation, restrictive licensing, or eventual abandonment.

Following established practice for HCI toolkit contributions [35, 52], we address four gaps in existing WBB software: infrastructure sustainability, community accessibility, extensibility, integration, and systematic requirements gathering. Rather than another specialized tool, we provide infrastructure aligned with established HCI toolkit goals [35] of reducing authoring complexity, integrating current practices, empowering new audiences, and enabling replication and creative exploration, grounded through co-design with 26 domain experts and delivered through cross-platform compatibility, extensible APIs, open-source MIT licensing, and self-contained deployment.

3 Co-Design and Requirements Analysis

To understand what infrastructure enables balance-based interaction across interactive applications, we conducted systematic requirements gathering with 26 expert users spanning posturography research and game development. Rather than designing for separate audiences, this co-design process treated balance data as both input modality for games and output measurement for assessment, revealing convergent infrastructure needs across both contexts.

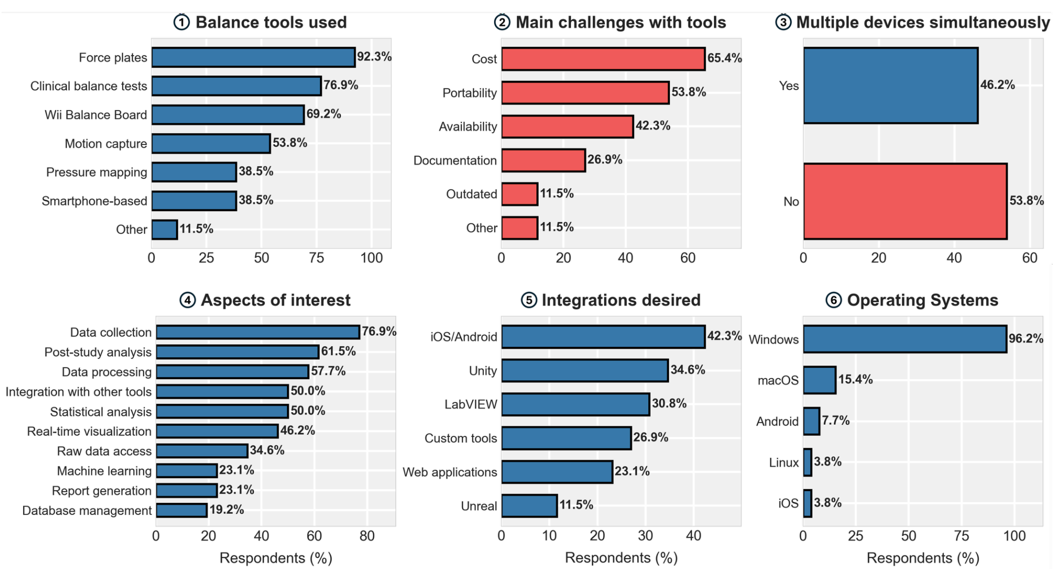

Fig. 2. Survey results. (1) "Which balance assessment tools do you currently use?" (2) "What are the main challenges you face when using balance assessment tools?" (3) "Do you use multiple balance devices simultaneously?" (4) "Which aspects are most important to you in a balance toolkit?" (5) "Which integrations would you like to see supported?" (6) "Which operating systems do you primarily use for balance-related work?"

3.1 Methodology

We designed a structured survey using Tally, targeting experts across balance-related disciplines including biomedical engineering, rehabilitation, sports science, human-computer interaction, and game development. The survey comprised 28 questions across five sections: demographics, experience with balance tools, research practices, technical preferences, and feature requirements. A total of 26 experts completed the survey and form the basis of the co-design analysis reported throughout this paper. Most structured questions allowed multiple selections, while open-ended responses captured additional insights on challenges and desired functionalities.

Participants were identified through systematic review of highly cited papers from the past decade on balance-based interaction, posturography, and balance rehabilitation in games and clinical settings, focusing on works employing force plates or Wii Balance Boards. Authors of qualifying papers were contacted by email with an anonymous survey link. Data collection occurred through the online survey with no follow-up interviews. This formative study approach reflects established practice in HCI toolkit research [35], where understanding target audiences prior to design helps avoid the “elastic user” problem and grounds toolkit goals in real community needs.

3.2 Participant Background and Current Practices

Participants represented diverse professional backgrounds with substantial expertise. Most identified as academic researchers (73.1%), with additional representation from clinical practitioners (11.5%), PhD students (7.7%), a physical therapist (3.8%), and a specialist physician in physical medicine and rehabilitation (3.8%). Geographic distribution spanned Europe (61.5%), North America (19.2%), South America (7.7%), Asia (7.7%), and the Middle East (3.8%). Experience levels were high, with 69.2% reporting over a decade of experience in their field. Self-rated posturography expertise was similarly strong: 34.6% identified as experts with specialised research or clinical experience, 23.1% as advanced, 23.1% as intermediate, and 19.2% as having basic knowledge of core concepts.

Current tool usage (Figure 2.1) revealed strong reliance on traditional equipment alongside growing WBB adoption. Research-grade force plates were used by 92.3% of participants and WBBs by 69.2%. Participants identified substantial challenges (Figure 2.2) when using balance assessment tools, with cost constraints reported by 65.4%, portability limitations by 53.8%, availability issues by 42.3%, inadequate documentation by 26.9%, and outdated software by 11.5%.

Satisfaction with existing WBB solutions averaged 3.3 out of 5. Initial setup and pairing issues affected 72.2% of users, while Bluetooth connectivity problems impacted 50.0%. Data accuracy concerns affected 44.4%, and software integration posed challenges for 38.9%. While hardware validation is strong, software infrastructure represents the primary adoption barrier across both clinical research and interactive applications.

3.3 Requirements for Balance-Based Interaction Tools

Feature prioritization and open-ended responses revealed five critical requirement themes bridging clinical research and game development needs.

Cross-Platform Connectivity and Reliability. Technical requirements (Figure 2.6) showed predominant Windows usage (96.2%) with meaningful macOS demand (15.4%). Most participants (88.5%) preferred offline systems over web-based solutions, citing reliability and data privacy concerns.

Design implication 1: Cross-platform support with automated Bluetooth pairing bypassing operating system UI, persistent connection status indicators, and local deployment without dependencies.

Real-Time Integration for Interactive Applications. Integration requirements (Figure 2.5) revealed clear priorities. Mobile applications topped needs (38%), followed by Unity integration (33%) and LabVIEW (29%). Web applications (24%) and custom programming interfaces (24%) represented additional needs. Qualitative responses emphasized transparent documentation, customizable pipelines, and stability for long-term use. Feedback highlighted low-latency requirements for real-time interaction, Unity integration for VR experiments, and portability for field testing.

Design implication 2: Real-time streaming via Lab Streaming Layer (LSL) for research integration and TCP for broader compatibility, with Unity and Python sample implementations demonstrating integration patterns and an Android companion application addressing the mobile integration priority (identified by 38% of participants).

Data Processing and Analysis Pipeline. Feature importance ratings (Figure 2.4) showed data collection capabilities ranked highest (76.9%), followed by post-collection analysis (61.5%), export and processing (57.7%), statistical analysis integration (50.0%), and real-time visualization (46.2%). Data format preferences converged on standards. CSV was preferred (73.1%), followed by Excel (34.6%) and MATLAB (34.6%). Participants emphasized flexible multi-format export, transparent metric calculations, reproducible processing, and ability to replay data with different parameters.

Design implication 3: Integrated pipeline from acquisition to visualization in a single application, standardized metrics with transparent documentation, CSV export for universal compatibility, and replay functionality enabling post-hoc parameter adjustment.

Multi-Device Support for Novel Mechanics. Interest in multi-board functionality (Figure 2.3) was substantial, with 46.2% expressing interest in simultaneous multi-device use. Use cases spanned clinical and interactive domains: expanded measurement areas, bilateral assessment, gait analysis, multi-person scenarios, and validation studies. This revealed critical gaps in existing single-board solutions and opportunities for both advanced clinical protocols and novel game mechanics like asymmetric multiplayer.

Design implication 4: Architecture supporting simultaneous multi-board connection with real-time visualization, persistent device naming for session continuity, and dual-board overlays enabling bilateral clinical assessment and novel gameplay configurations.

Open and Sustainable Infrastructure. Participants emphasized sustainable, maintainable infrastructure. Technical preferences strongly favored offline systems over web-based solutions, with concerns about server dependency after experiencing discontinued tools. Integration preferences revealed desire for extensibility. While standalone functionality was essential, participants needed APIs and coding support for custom workflows. The combination of offline operation, open-source licensing, and extensible APIs emerged as critical for long-term sustainability.

Design implication 5: MIT licensing enabling community contributions, GitHub hosting for transparent development, comprehensive documentation of processing pipelines and metrics, and extensible architecture allowing integration without modifying core codebase.

3.4 Synthesis

Requirements analysis revealed convergence between clinical researchers and interactive developers. Both communities require reliable cross-platform connectivity, real-time data access, transparent processing, and sustainable infrastructure. Differences were manifest in application context rather than fundamental capabilities: clinical researchers emphasized validated protocols, reproducible analysis, and robust data collection and processing pipelines, while game developers prioritized real-time data streaming, visualization, and game engine integration. These distinctions represent different uses of shared infrastructure rather than conflicting requirements.

This convergence validates our ecosystem-first design philosophy and maps directly onto the toolkit goals identified by Ledo et al. [35]: DI1 and DI2 address reducing authoring complexity and integrating with current practices, DI3 creates paths of least resistance for data analysis workflows, DI4 enables replication and creative exploration through multi-device support, and DI5 empowers new audiences through open and sustainable infrastructure. Rather than optimizing for narrow use cases, we designed comprehensive infrastructure serving both communities through modular architecture, standardized interfaces, and extensible APIs.

4 The Balance Toolkit

The Balance Toolkit translates the five design implications identified through co-design into practical infrastructure serving both developers and posturography researchers. Following Ledo et al.'s definition of toolkits as generative platforms [35], the toolkit provides permutable building blocks (device connectivity, streaming protocols, processing pipelines, and activity templates) that developers and researchers can combine and adapt rather than re-implement from scratch. We describe the system architecture, integration capabilities, data processing pipeline, and user interface supporting diverse workflows.

4.1 System Architecture

The toolkit architecture separates hardware communication, data processing, user interaction, and external APIs into modular layers (DI5). This structure manages multiple concurrent events originating from diverse sources: Bluetooth device discovery, balance board input and output, replay execution, user interface interactions, TCP and LSL data transmission, and file system operations.

We adopted an event-driven actor model implemented with the Tokio asynchronous runtime for Rust. This approach ensures tasks from independent sources can be scheduled and executed efficiently while maintaining user interface responsiveness and data stream consistency. The architecture scales to demanding scenarios such as dual-board sessions, where two boards operate in parallel while the application streams raw and processed data to four independent channels (two TCP and two LSL), writes to four files on disk, and renders four visualization streams in the interface. Both boards are timestamped using the host machine's monotonic clock when each HID report is received, providing a common temporal reference without requiring drift correction. Residual skew is bounded by host OS scheduling jitter and the WBB's 10 ms native sampling interval.

The technology stack combines a Rust backend for performance and memory safety with a React frontend for flexibility and rapid iteration. This architecture produces lightweight native builds for Windows, macOS, and Linux through Tauri (DI1). Offline-first deployment without external dependencies satisfies the strong preference for local systems expressed during co-design. The project is fully open source under MIT license and hosted on GitHub with comprehensive documentation of all metric calculations and workflows (DI5).

4.2 Device Connectivity

The system queries all available Bluetooth adapters and aggregates device lists, applying name-based filtering to identify devices matching "Nintendo RVL-WBC-01". Upon detecting an unpaired device, the system initiates automated pairing using the host Bluetooth adapter's MAC address for authentication (DI1). For a host with MAC address M, PIN generation follows:

$$PIN[i] = M[5-i] \quad \forall i \in [0,5] \tag{1}$$

This byte-order reversal transforms the host MAC address into the required six-byte PIN according to Nintendo's Wii Remote pairing specification. Since the WBB uses Bluetooth 2.0, a legacy protocol lacking adequate cross-platform library support, the application implements platform-specific handlers accommodating varying system constraints across operating environments. Combined with persistent connection status indicators in the interface, this automated approach eliminates manual pairing through operating system interfaces.

4.3 Data Processing Pipeline

The processing pipeline transforms raw sensor readings into validated metrics through configurable stages, serving both interactive feedback and assessment requirements (DI3). All data processing was adapted from standard posturography protocols and prior work in the literature.

4.3.1 Center of Pressure Computation. Following previous protocols [34], given force readings from sensors at platform corners (top-left F_{TL}, top-right F_{TR}, bottom-left F_{BL}, bottom-right F_{BR}) as shown in Figure 3, the center of pressure coordinates are computed from the total applied load (Equation 2) as given in Equations 3 and 4:

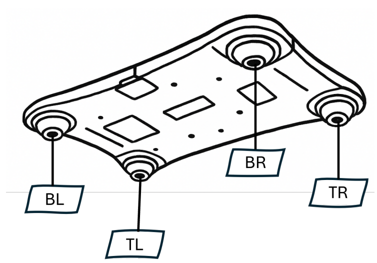

Fig. 3. Force sensor placement in the balance board. Four sensors are located at the corners: top-left (TL), top-right (TR), bottom-left (BL), and bottom-right (BR), used to compute the center of pressure (CoP).

$$F_{total} = F_{TL} + F_{TR} + F_{BL} + F_{BR} \tag{2}$$

$$CoP_x = \frac{(F_{TR} + F_{BR}) - (F_{TL} + F_{BL})}{F_{total}} \tag{3}$$

$$CoP_y = \frac{(F_{TR} + F_{TL}) - (F_{BR} + F_{BL})}{F_{total}} \tag{4}$$

where CoP_x (3) represents center-of-pressure medial-lateral displacement and CoP_y (4) represents anterior-posterior displacement, both dimensionless and ranging from −1 to 1. Physical coordinates in millimetres can be recovered by multiplying by the board's half-dimensions (114 mm medial-lateral, 216.5 mm anterior-posterior) [34]. When the total force F_{total} (2) falls below 0.1 kg, CoP is set to origin (0,0) to handle noise in low-force conditions. CoP coordinates (expressed in meters relative to board center) serve as the primary control signal for balance-driven interaction, mapping body sway to cursor movement, avatar control, or navigational input, and equally as the foundational input for posturographic assessment of standing balance and weight distribution.

4.3.2 Temporal Resampling. Wireless transmission introduces sampling jitter, producing irregular intervals, as reported in previous studies [53]. The toolkit resamples data using one of three configurable methods. Linear interpolation connects consecutive points with straight segments, efficient for real-time use. Cubic spline interpolation provides smooth curves with continuous derivatives, better suited for offline analysis. Polynomial interpolation applies local Lagrange polynomials in sliding windows, capturing complex motion without global high-order instability. Method selection balances computational cost against signal fidelity requirements for specific applications. Consistent sampling is essential for valid posturographic comparison across trials and participants, while for interactive applications it ensures smooth, predictable input mapping without perceptible lag or stutter. Bluetooth dropouts exceeding 500 ms trigger automatic reconnection with the gap logged in the data. Packet loss results in missing samples left for downstream handling, as outlier rejection and drift correction strategies are application-dependent.

4.3.3 Stability Metrics. The toolkit computes both basic and advanced stability measures. The Stability Index (SI) [17] quantifies root-mean-square displacement from mean CoP position:

$$SI = \sqrt{\frac{1}{N}\sum_{i=1}^{N}[(CoP_{x,i} - \overline{CoP_x})^2 + (CoP_{y,i} - \overline{CoP_y})^2]} \tag{5}$$

The Dynamic Postural Stability Index (DPSI) [72, 74] extends this through directional components. Medial-lateral stability (MLSI) quantifies frontal plane fluctuations:

$$MLSI = \sqrt{\frac{1}{N}\sum_{i=1}^{N} CoP_{x,i}^2} \tag{6}$$

Anterior-posterior stability (APSI) measures sagittal plane fluctuations:

$$APSI = \sqrt{\frac{1}{N}\sum_{i=1}^{N} CoP_{y,i}^2} \tag{7}$$

Vertical stability (VSI) quantifies total force variations:

$$VSI = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(W_{baseline} - F_{total,i})^2} \tag{8}$$

These components combine into a composite DPSI score providing a complete stability assessment with higher values indicating greater instability. In interactive applications, these indices enable adaptive difficulty scaling, real-time performance feedback, and skill progression systems, while in posturography they quantify balance impairment and track rehabilitation progress across sessions.

4.3.4 Spatial Metrics. Area-based metrics capture spatial extent of postural sway. The 95% confidence ellipse [61] represents the region containing most data points, computed from covariance matrix eigenvalues using chi-square critical value (5.991 for 95% confidence with 2 degrees of freedom). The convex hull describes the smallest polygon enclosing all points using Graham's scan algorithm [67], providing maximum boundary of sway excursions. For interactive applications, these area measures inform play zone boundaries, target sizing, and movement range calibration per user, while in clinical settings they quantify postural control capacity and detect asymmetries.

4.3.5 Frequency Analysis. Frequency domain analysis [5, 63] reveals oscillatory patterns through Fast Fourier Transform on windowed signals. The toolkit applies Hann windowing to reduce spectral leakage and computes one-sided amplitude spectrum with coherent gain correction. Combined directional spectrum integrates both medial-lateral and anterior-posterior components:

$$A_{xy}(k) = \sqrt{A_x(k)^2 + A_y(k)^2} \tag{9}$$

Typical analysis focuses on frequencies up to 2 Hz capturing physiologically relevant postural sway dynamics, distinguishing low-frequency components linked to visual and vestibular control from higher frequencies reflecting proprioceptive and cerebellar mechanisms. This decomposition enables frequency-aware game mechanics that selectively respond to specific postural control strategies and supports clinical identification of sensory integration deficits.

4.4 Mobile Companion Application

The Android companion application (Figure 4) extends the Balance Toolkit to mobile contexts, enabling portable data collection without a desktop computer. The app replicates the desktop processing pipeline with configurable window size, sliding window overlap, and sampling rate,

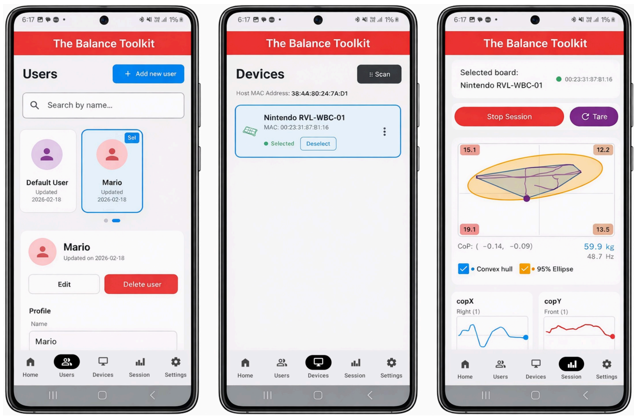

Fig. 4. The Balance Toolkit Android companion application showing (left) user management, (center) device scanning and selection, and (right) a live session with real-time CoP trajectory, force readings, and displacement time-series.

and provides real-time visualizations of center of pressure coordinates, velocity components, FFT amplitude spectrum, and DPSI metrics. The Activities menu is omitted as the mobile form factor cannot accommodate a participant-facing instruction screen. All raw data exports to CSV and can be imported into the desktop application for post-hoc analysis with modified processing parameters.

However, iOS support is not feasible because Apple's Core Bluetooth SDK exclusively handles Bluetooth Low Energy (4.0+) devices [3], while the WBB uses Bluetooth 2.0 Classic. The IOBluetooth framework supporting Classic Bluetooth is restricted to macOS [4], and relying on undocumented private APIs would introduce unacceptable fragility. On Android, standard APIs support pairing and PIN configuration, but HID connection APIs are restricted to system applications. The toolkit circumvents this by intercepting HID reports from the operating system rather than establishing direct HID connections. This polling-based mechanism results in a lower data acquisition frequency of approximately 40 Hz compared to the 100 Hz push-based desktop communication.

A significant caveat applies to long-term Android support. Previous open-source WBB connectivity projects for Android have ceased functioning as the platform evolved, and each Android version has historically introduced Bluetooth protocol changes that can break existing workarounds. The current implementation supports Android 13 through 16, but sustained compatibility remains an ongoing maintenance challenge.

4.5 Game Engine Integration

Real-time integration capabilities distinguish the Balance Toolkit from previous WBB solutions (DI2). The toolkit provides dual streaming protocols and ready-to-use implementation examples for Unity and Python.

4.5.1 Streaming Protocols. The toolkit provides two parallel streaming channels. Lab Streaming Layer (LSL) offers high-level channel abstraction suitable for integration with research frameworks including MATLAB, Python, and established physiological monitoring systems. Transmission Control Protocol (TCP) provides raw binary format for direct inspection and custom processing, with lower overhead for performance-critical applications.

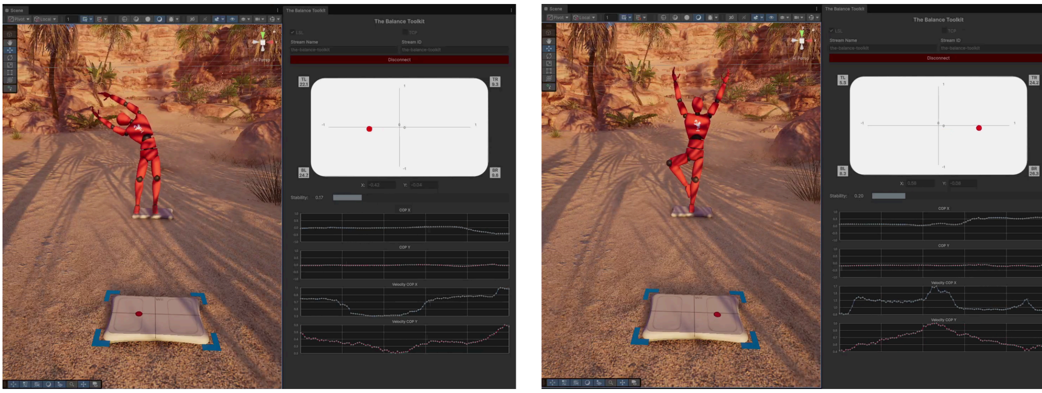

Fig. 5. Unity integration sample demonstrating real-time Balance Toolkit data visualization. Left: 3D scene with virtual balance board showing the real-time center of pressure position (red circle) and yoga-pose avatar for interactive balance training applications. Right: Unity editor panel displaying live balance metrics including force sensor readings, center of pressure coordinates, velocity components, and stability indices.

Both protocols expose two streams sampled at 100 Hz. The basic stream provides timestamp, device MAC address, four force sensor readings ($F_{TR}, F_{BR}, F_{TL}, F_{BL}$), and center of pressure coordinates (CoP_x, CoP_y). The complex stream adds velocity components (v_{CoP_x}, v_{CoP_y}), stability index, and four directional stability indices (DPSI$_{MLSI}$, DPSI$_{APSI}$, DPSI$_{VSI}$, DPSI$_{overall}$). This dual-stream architecture provides raw sensor access for novel processing and validated metrics for use.

4.5.2 Unity Integration. We provide a complete Unity sample project demonstrating balance-based interaction for game development (Figure 5). The sample includes a dedicated editor window providing real-time visualization of force sensors, center of pressure coordinates, velocity components, and overall stability index. A MonoBehaviour script illustrates data access during Play Mode, mapping balance data to scene objects.

The example scene displays a virtual balance board with red circle indicating real-time center of pressure, alongside an avatar performing yoga poses. This demonstrates how postural sway and stability measures change dynamically in response to movement, providing a foundation for developers to explore balance-controlled VR locomotion, weight-shifting game mechanics, and postural challenge systems. The implementation uses both LSL and TCP connections, allowing developers to choose the appropriate protocol for their performance requirements.

4.5.3 Python Integration. Two Python scripts demonstrate LSL and TCP access patterns for analysis pipelines and machine learning workflows. The LSL interface provides channel abstraction that matches research frameworks, while the TCP implementation provides direct binary packet handling for performance-critical processing. Both scripts include complete connection handling, data parsing, and example visualization, enabling researchers and developers to rapidly prototype custom processing without reverse-engineering protocols.

4.6 User Interface

The desktop application provides six main menus supporting workflows spanning assessment and interactive development: Home, Users, Devices, Session, Replay, and Activities. Figure 6 illustrates the Session interface showing real-time visualization and control options.

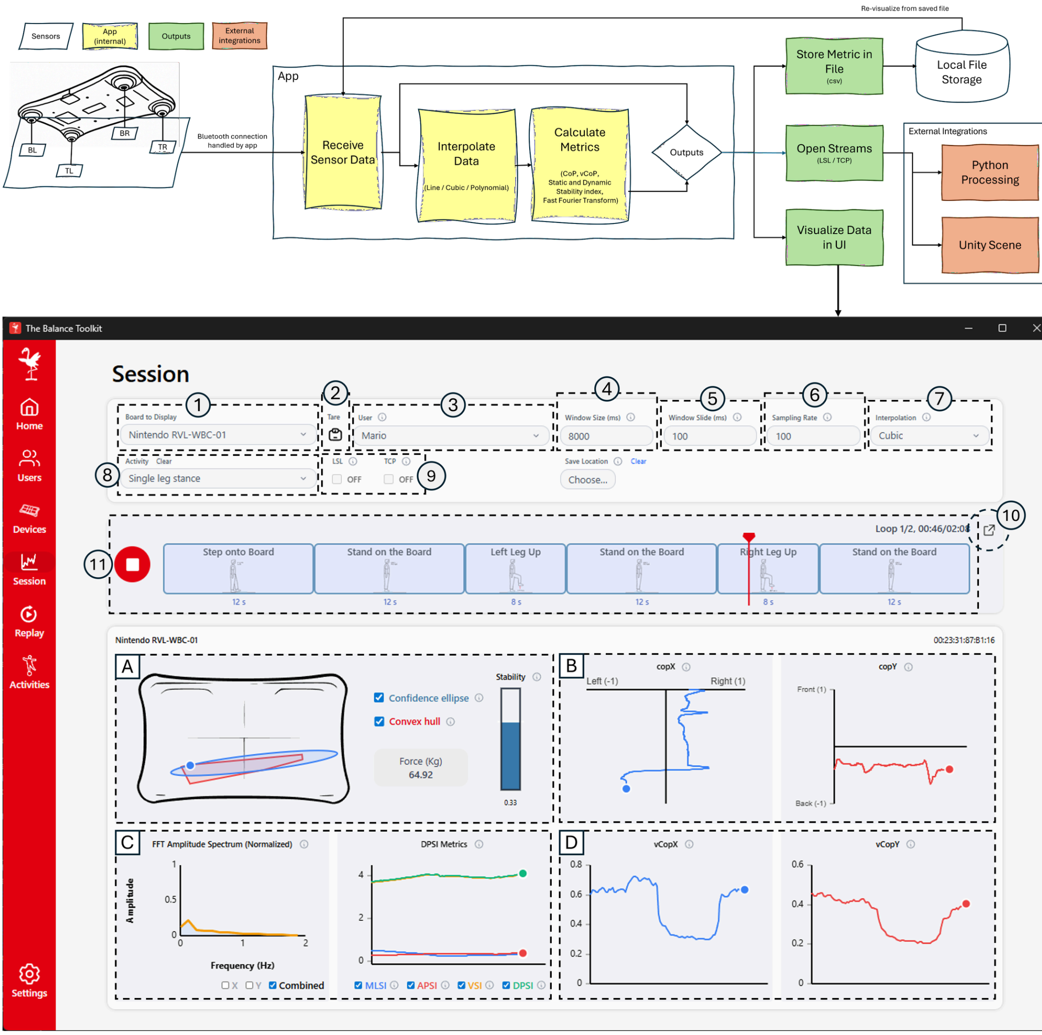

Fig. 6. Overview of the Balance Toolkit session interface. Top: data processing workflow from sensor inputs through interpolation to metric calculations. Bottom: session configuration panel and real-time visualization of balance metrics including center of pressure trajectories, confidence ellipses, frequency spectra, and stability indices.

4.6.1 *Session Interface.* The Session menu (Figure 6) supports recording from one or two WBBs with comprehensive real-time visualization and structured configuration controls. Users select and tare connected boards, associate a predefined user profile with the recording, and configure processing parameters including window size, sliding window overlap, sampling rate (100 Hz by default, matching the native WBB rate), and interpolation method (linear, cubic, or polynomial). An optional predefined activity inserts event markers into the data stream. Real-time data transmission can be activated through LSL, TCP, or both simultaneously. A secondary pop-up window can display visual task instructions on a participant-facing monitor, and a timeline visualization indicates the current position within the selected activity protocol throughout the session.

Real-time visualization includes four coordinated panels: (A) center of pressure trajectory on platform surface with confidence ellipse and convex hull overlays alongside stability index display, (B) time-series plots of CoP displacement in medial-lateral and anterior-posterior directions, (C) frequency domain analysis through FFT amplitude spectrum and Dynamic Postural Stability Index metrics visualization, and (D) velocity components of center of pressure movement over time. This multi-panel approach serves both researchers monitoring data quality and developers observing real-time response to balance input.

4.6.2 User and Device Management. The Users menu (Figure 7) manages participant profiles, including metadata such as name, age, gender, height, weight, dominant hand, and color coding. Weight can be captured directly from board readings, streamlining setup for both clinical protocols and game testing sessions. The Devices menu (Figure 8) enables scanning for available WBBs, with LED identification helping distinguish multiple boards. Custom board naming persists across sessions, addressing confusion when multiple identical devices are present (DI4).

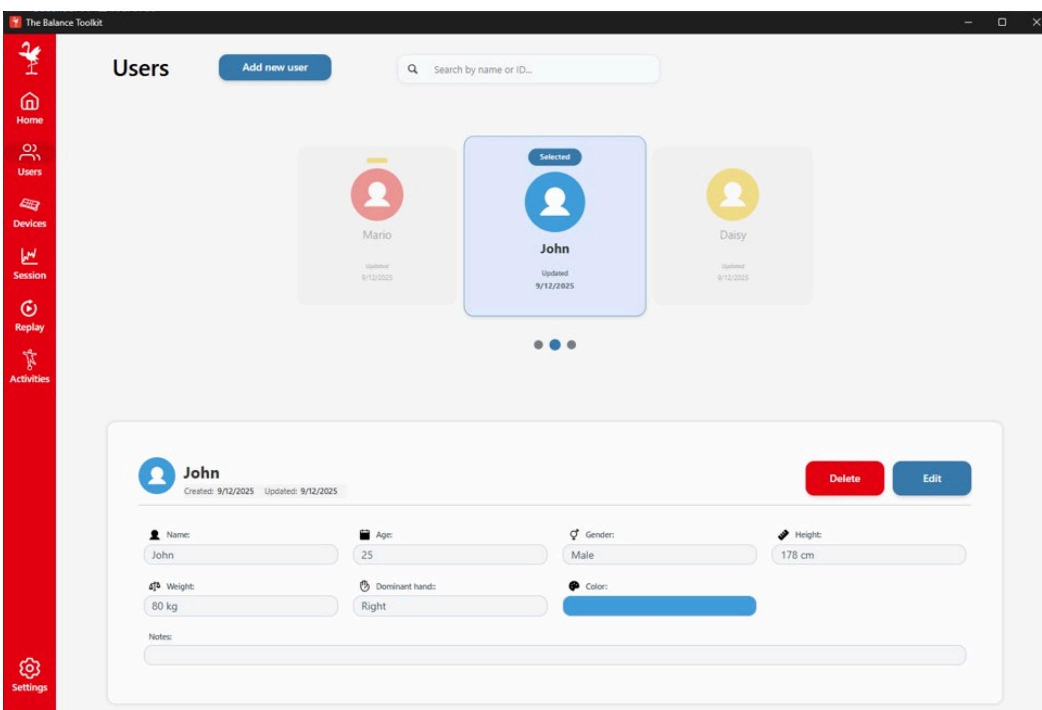

Fig. 7. User management interface. The application allows adding, selecting, editing and deleting user profiles with metadata information.

4.6.3 Activities Templates. The Activities menu (Figure 9) provides six activity templates based on established posturography protocols adaptable for both balance assessment and game mechanics: Eyes Open-Close, Functional Reach Test, Single Leg Stance, Tandem Stance, Timed Up and Go, and Squat, which are protocols well-validated in the literature [16, 30, 55, 56]. Each template includes illustrated task phases with customizable timing and sequencing. Users can reorder actions, edit durations by dragging block borders or double-clicking to enter direct input, add custom actions, and specify repetition counts.

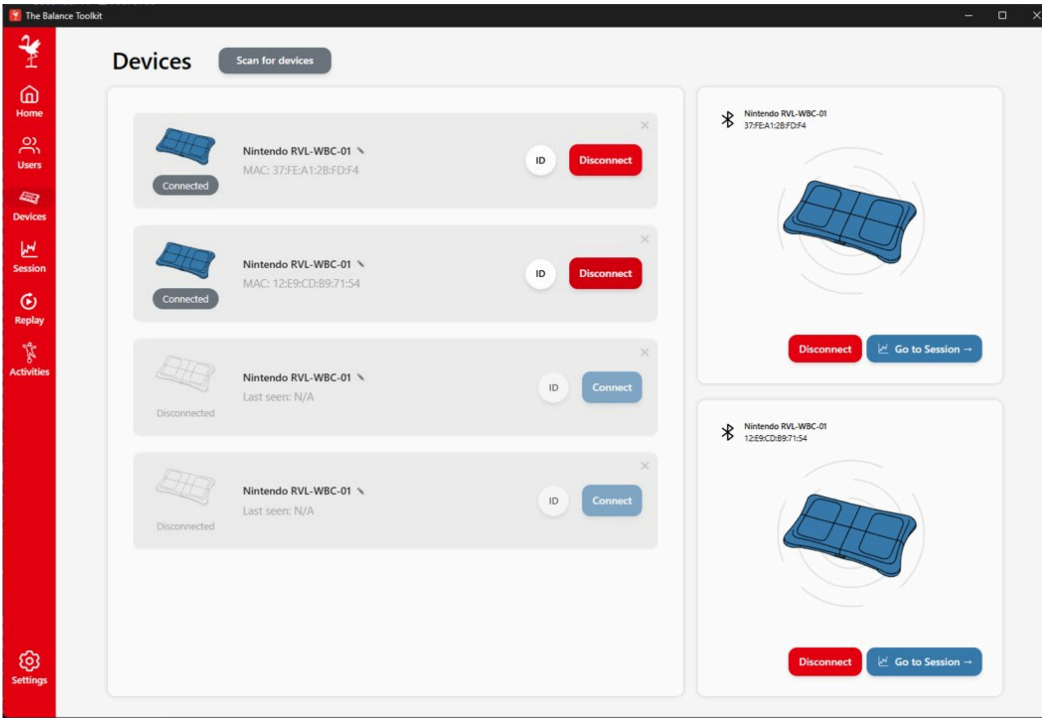

Fig. 8. Device management interface. Left: device list showing connected and available Wii Balance Boards, with options to scan for devices, identify a board via LED blinking, and connect or disconnect. Right: per-board connection cards for a dual-board configuration, each showing the board render and a link to start a session.

These templates serve dual purposes. For game developers, they offer validated challenge structures with known difficulty progressions, enabling rapid prototyping of balance-based game mechanics without requiring posturography expertise. For balance researchers, they provide standardized protocols with automatic event logging. The visual instruction system supports both player-facing game tutorials and participant-facing clinical assessments.

4.6.4 Replay and Analysis. The Replay menu (Figure 10) loads previously recorded sessions with associated settings, enabling post-hoc analysis with modified parameters. Users can adjust window size, sliding window parameters, and interpolation methods after original experiments are concluded (DI3). Replayed data can be streamed through LSL or TCP, integrating past datasets into real-time pipelines for comparative analysis or game mechanic iteration.

4.7 Implementation for Sustainability

Beyond functional requirements, the toolkit prioritizes long-term maintainability through deliberate architectural and process decisions (DI5). The modular architecture isolates hardware communication, data processing, user interface, and external APIs, enabling independent component evolution. Comprehensive documentation covers all metric calculations with mathematical formulations, processing stages with parameter effects, and integration patterns with working examples (DI3).

The development workflow employs semantic versioning for API stability and automated release builds ensuring consistent packaging. GitHub issue templates guide bug reports and feature requests, while contribution guidelines lower barriers for community participation.

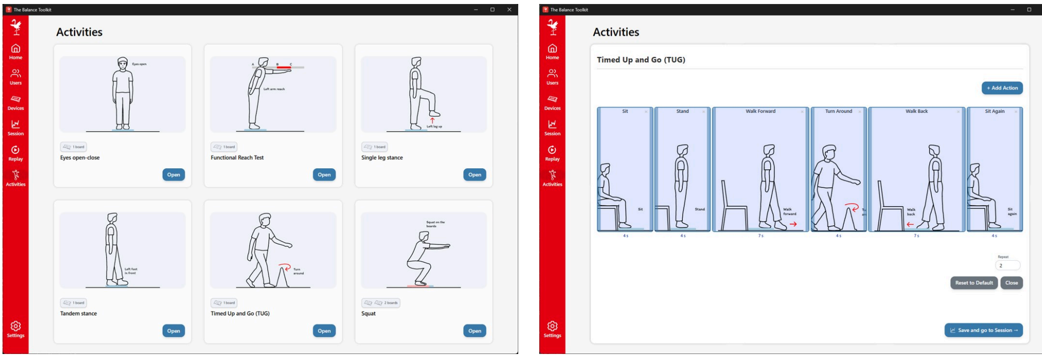

Fig. 9. Activities management interface in the Balance Toolkit. Left: overview of six standardized posturography protocols with illustrated activity cards showing "Eyes Open-Close," "Functional Reach Test," "Single Leg Stance," "Tandem Stance," "Timed Up and Go," and "Squat" exercises. Right: detailed workflow editor for the "Timed Up and Go" activity showing sequential action blocks with customizable timing and visual instructions.

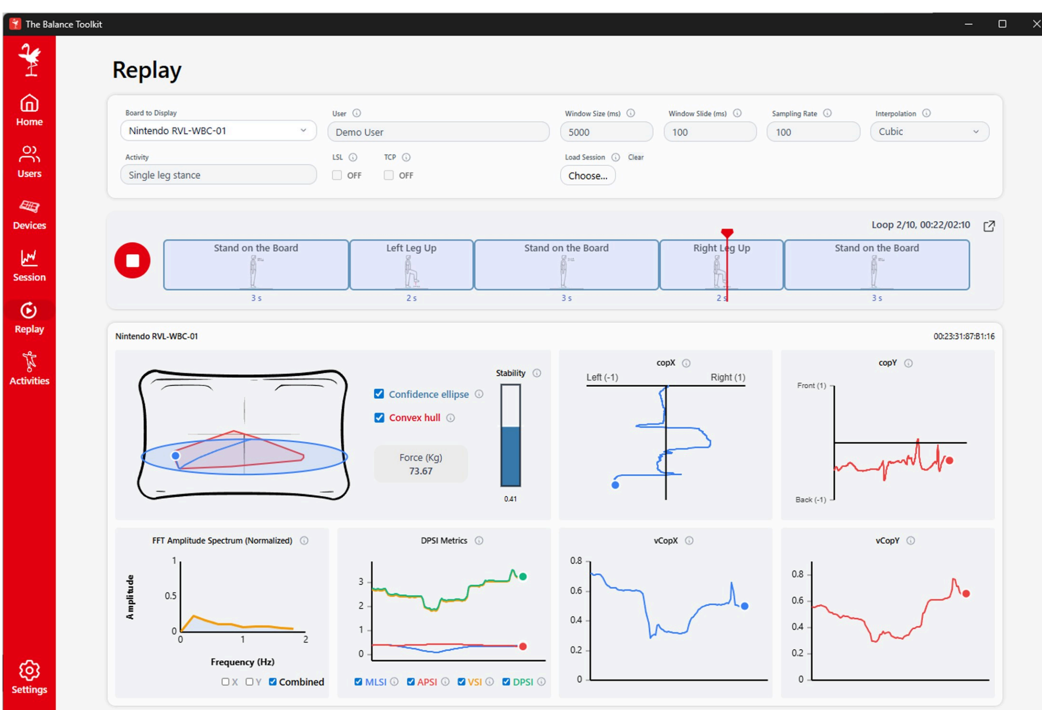

Fig. 10. Replay management interface in the Balance Toolkit. Top: device, session, and activity selection with data adjustment controls. Middle: timeline showing Single Leg Stance activity sequence with durations. Bottom: real-time visualization of center-of-pressure trajectories, stability metrics, displacement plots, frequency spectrum, and velocity analysis.

5 Evaluation

We evaluated the Balance Toolkit through three complementary strategies drawn from Ledo et al.'s taxonomy of HCI toolkit evaluation [35]: *demonstration* (Android port and Unity and Python integration samples illustrating how balance signals reach external applications through standard streaming protocols), *technical performance* (connection stability and latency benchmarks across operating systems), and *usage* (a first-use study [24] examining task completion and perceived usability with domain specialists).

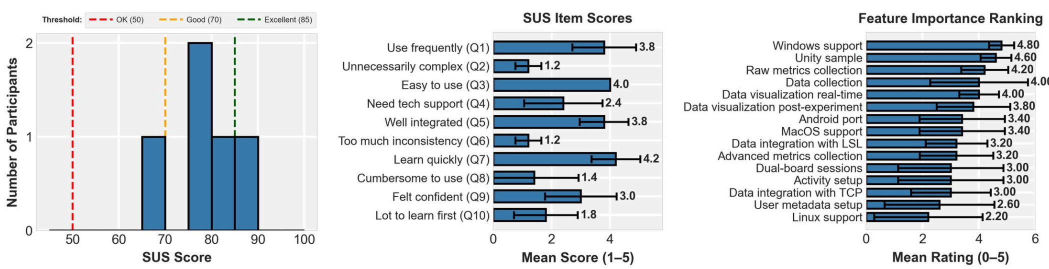

Fig. 11. Results from first-use study. **Left**: the SUS score distribution with reference thresholds (OK=50, Good=70, Excellent=85). **Centre**: the mean SUS item scores (1–5) with error bars. **Right**: the mean feature-importance ratings (0–5) ranked by importance.

5.1 Performance Benchmarks

We assessed connection stability and end-to-end latency through repeated trials across Windows, macOS, Linux, and Android. All experiments used the same toolkit build and session settings. The macOS tests ran on a MacBook Air (Apple M1, 8 GB, macOS Sequoia 15.6), Linux on a Beelink SER9 Pro (AMD Ryzen 7 255H, Arch Linux kernel 6.16.6), Windows on a desktop PC with an ASUS TUF GAMING B560-PLUS WIFI motherboard, Intel Core i7-11700 CPU, 32 GB RAM, and an NVIDIA GeForce RTX 3060 GPU running Windows 11 Home (Build 26100), and Android on a Samsung Galaxy S21 Ultra (256 GB, Android 15). Bluetooth adapters varied by platform: Intel AX200 (Bluetooth 5.2) on Linux, proprietary Apple adapter (Bluetooth 5.0) on macOS, and the onboard adapter from the ASUS TUF GAMING B560-PLUS WIFI motherboard (Bluetooth 5.0) on Windows.

For connection tests, each platform completed ten cycles of scanning, syncing, connecting, running a two-minute session with a researcher standing on the board, and removing the device. Detection and connection times were measured from sync button press to confirmed connection. Mid-session reliability was assessed by monitoring for gaps longer than 500 ms, which triggered automatic recovery. For latency tests, each platform performed ten two-minute sessions under identical conditions. Latency was defined as time from decoded HID report reception to availability at four sinks (Rust backend, TCP transport, LSL outlet, and frontend UI). External LSL and TCP clients measured reception times against the original timestamp using a monotonic clock.

We evaluated the performance (P) of the Balance Toolkit across operating systems through research questions about stability and latency:

P-RQ1 (Connection stability): How reliably and quickly can the Balance Toolkit detect and establish connections with the WBB, and how stable are connections during active sessions?

	Connection Rate	Median Connect Time	Mid-session Disconnects
Windows	100%	1.91 s	0
ArchLinux	100%	2.64 s	0
macOS	100%	5.12 s	0
Android	100%	1.64 s	0

Table 1. Connection performance of WBB with The Balance Toolkit across operating systems and mobile platforms.

P-RQ2 (Latency performance): What are the end-to-end latencies from sample entry to availability at the on-screen UI, the LSL outlet, and the TCP outlet, and how do they vary across operating systems?

5.1.1 Connection Stability (P-RQ1). All platforms achieved a 100% connection rate with no mid-session disconnects, and differed mainly in connection speed and setup requirements. Android and Windows connected fastest (1.64 s and 1.91 s median), followed by Linux (2.64 s) and macOS (5.12 s). Linux required additional manual `hidraw` configuration, and Android required Bluetooth permissions to be granted at runtime, while Windows and macOS functioned without extra setup steps. The macOS connection time, while the slowest, is a one-time setup cost at the start of a session, after which sessions remain stable. Reported connection numbers also depend on host Bluetooth adapter quality, which varies widely across machines.

5.1.2 Latency Performance (P-RQ2). Backend and transport latencies were negligible across all platforms, remaining well below 0.5 ms (see Table 2 for per-platform values). Linux achieved the lowest latencies at backend and transport layers, while macOS excelled at the frontend. The frontend consistently dominated overall delay across all platforms, ranging from 5.92 ms on macOS to 12.71 ms on Windows, suggesting that application-level optimizations would yield the greatest performance gains for interactive applications.

5.2 Usability Study

Five participants (P1–P5) representing the toolkit's intended cross-disciplinary use took part in a first-use evaluation. None had participated in the earlier expert survey, separating broad feature preferences from first-time interaction behaviors. **P1** (male, ~38, 10 years of experience) was an HCI researcher working on adaptive systems using physiological sensing. **P2** (male, ~22, 3 years of professional experience) was a motion-analysis researcher using IMUs and optical capture with athletes in ACL rehabilitation. **P3** (male, ~25, 6 years of experience) was a VR developer with cross-platform experience in Windows and Android. **P4** (female, ~35, 7 years of experience) was a biomechanics engineer working with force plates and populations including cerebral palsy and Parkinson's disease. **P5** (male, ~45, 15 years of experience) was an academic researcher working on interactive applications for gait analysis in children with cerebral palsy.

Each session took approximately 30 minutes on a Windows 11 laptop with the toolkit pre-installed. After a brief purpose overview with no interface walkthrough, participants completed three minutes of free exploration while thinking aloud, followed by five scenarios covering core functionality: (1) connecting a WBB and starting a session, (2) creating a participant profile and

OS	Layer	Mean (ms)	STD	CI 95%
Windows	Rust	0.22	0.10	0.20–0.24
	TCP	0.37	0.13	0.37–0.38
	LSL	0.46	0.19	0.46–0.47
	Frontend	12.71	5.68	12.60–12.82
Linux	Rust	0.18	0.06	0.18–0.18
	TCP	0.28	0.09	0.28–0.29
	LSL	0.35	0.11	0.35–0.36
	Frontend	10.11	4.76	10.08–10.28
macOS	Rust	0.18	0.11	0.18–0.18
	TCP	0.34	0.15	0.33–0.33
	LSL	0.42	0.22	0.40–0.41
	Frontend	5.92	2.98	5.85–5.99

Table 2. Latency benchmarks across operating systems and communication layers.

recording body weight from the board, (3) monitoring real-time balance on the dashboard, (4) configuring a TUG activity with custom phases including reordering and inserting a breathing phase, and (5) replaying a completed session. Tasks were presented one at a time on a printed task sheet, and the moderator intervened only if a participant was blocked for over two minutes. A researcher annotated Norman's Gulfs of Execution and Evaluation throughout each session.

After completing the scenarios, participants reviewed integration options (Python LSL/TCP scripts, Unity sample, exported formats) and completed a structured post-task protocol consisting of the System Usability Scale (10 items, 5-point Likert), comparative questions on how the toolkit relates to tools they currently use and in which scenarios they would choose it over commercial systems, feature-importance ratings on a 0–5 scale across real-time visualization, CSV export, MATLAB and Excel integration, calibration feedback, multi-device support, and Unity integration, scenario mapping in which participants identified the contexts where each feature would matter, an open prompt on what one feature they would add, and an adoption-barriers prompt on what would stop them from using the toolkit in their daily work. The session closed with a brief debriefing in which participants ranked the most critical issues they encountered.

We evaluated the usability (U) of the Balance Toolkit through three research questions:

U-RQ1 **(Usability):** Can first-time users from relevant research and development domains complete core tasks without prior training?

U-RQ2 **(Feature relevance):** Which features were considered most valuable across contexts of use?

U-RQ3 **(Adoption):** Under what circumstances would participants decide to use the Balance Toolkit together with the *WBB*, and what factors would prevent them from doing so?

5.2.1 Workflow Completion (U-RQ1). This evaluation focused on workflow discoverability for first-time users rather than feasibility, since technical feasibility (whether boards connect, whether sessions record, whether data streams) is established by the performance benchmarks reported earlier. All participants completed every workflow without assistance and described the interface as "professional" and "cool," yet recurring issues reduced confidence.

Entry point for recording was unclear. The Start/Record control was consistently overlooked. P1 and P2 hesitated due to low salience relative to configuration controls, P3 and P4 confused the replay and record icons, and P5 searched the toolbar rather than the sidebar. This produced a *gulf of execution* in locating the recording entry point and a *gulf of evaluation* from absent state cues such as "Recording" or "Saved."

Actions lacked confirmation feedback. P1 and P3 clicked Save but received no closure, while P2 and P5 double-checked multiple screens to confirm edits. The uncertain action sequence (Start → Stop → Save) created an *execution gulf*, and absent success messages reduced trust in data persistence, forming an *evaluation gulf.*

Editing and reordering were difficult to discover. All participants attempted to insert a custom "Breathe" action. P1–P3 found custom entry and ordering non-obvious, sometimes breaking routines, while P4 and P5 encountered scaling issues that obscured controls. Editing affordances were non-discoverable (*execution gulf*), and absent edit previews required manual cross-checks (*evaluation gulf*).

Device connection status was inconsistent. P1 noted confusion around the Scan → Select → Connect sequence and premature "Connected" labels. P3 looked across screens for a persistent status badge, and P4 could enter a session without creating a user profile. Prerequisites for connection were unclear (*execution gulf*) and readiness indicators were inconsistent (*evaluation gulf*).

Jargon and scaling issues hindered usability. UI scaling issues (clipped buttons, hidden scroll affordances) affected P4 and P5. Technical terms such as LSL/TCP, "window size," and "loops" surfaced before basic success was achieved, increasing cognitive load and forcing guessing (*execution and evaluation gulfs*).

The **mean SUS score** (Figure 11) was $M = 77.0$ ($SD = 8.2$, range = 65.0–87.5), indicating *good* and *acceptable* usability [7].

5.2.2 Feature Relevance (U-RQ2). Feature-importance ratings were collected at the end of each session and reflect participants' perceived priorities during first-use rather than measured value across sustained workflows. We present them as design signals about which capabilities first-time users gravitate toward, not as empirical validation of feature utility. Within this framing, the ratings showed clear stratification. Windows support ($M = 4.8$, $SD = 0.5$) and Unity integration ($M = 4.6$, $SD = 0.6$) ranked highest, followed by raw metrics collection ($M = 4.2$, $SD = 0.8$), data collection ($M = 4.0$, $SD = 1.7$), and real-time visualization ($M = 4.0$, $SD = 0.7$). Mid-tier features included post-experiment visualization ($M = 3.8$, $SD = 1.3$), Android port ($M = 3.4$, $SD = 1.5$), macOS support ($M = 3.4$, $SD = 1.5$), LSL integration ($M = 3.2$, $SD = 1.1$), and advanced metrics ($M = 3.2$, $SD = 1.3$). Dual-board sessions, activity setup, and TCP integration were rated situationally valuable ($M = 3.0$), while user metadata setup ($M = 2.6$, $SD = 2.0$) and Linux support ($M = 2.2$, $SD = 1.9$) ranked lowest. Feature ranking can be seen in Figure 11 (right).

5.2.3 Adoption Conditions (U-RQ3). Interview feedback identified both motivators and barriers for toolkit adoption. P1 emphasized low-latency feedback as essential for real-time interaction without perceptible delay. P2 highlighted portability and lightweight computation, noting suitability for athlete testing in field settings. P3 pointed to Unity integration as enabling VR locomotion experiments driven by naturalistic body input, potentially reducing cybersickness compared to head-driven locomotion. P5 noted adoption would be facilitated by validation metrics beyond CoP, specifically ground reaction forces for cross-checking sensor accuracy.

On the barrier side, P4 would not adopt the toolkit due to reliance on high-grade equipment and identified absent calibration as decisive: "Calibration is critical; devices drift and need to recalibrate periodically." P5 reinforced this, noting calibration using weights, instrumented poles, and frame alignment was non-negotiable in gait analysis research. Sensor accuracy concerns, connectivity robustness, and UI scaling issues were raised across multiple participants as adoption barriers.

5.3 Summary

Performance benchmarks showed that all platforms can reliably connect to the WBB, with Windows offering the fastest and most stable connections, Linux achieving the lowest backend and transport latencies, and macOS excelling at the frontend layer. Backend and transport latencies remained below 0.5 ms across all platforms, while frontend delays dominated at 5.92–12.71 ms.

Usability testing showed that participants completed all workflows without assistance, rating the toolkit as *good* and *acceptable* on the SUS scale ($M = 77.0$, $SD = 8.2$, 73rd percentile). Five usability themes emerged around recording entry points, action feedback, activity editing, connection status, and technical jargon. Feature ratings highlighted strong demand for Windows support and Unity integration, followed by raw metrics collection and real-time visualization. Adoption interviews pointed to low-latency feedback, portability, and workflow integration as key drivers, while calibration, sensor accuracy, and connectivity robustness were identified as primary barriers. These findings suggest three development priorities: improving interface discoverability and feedback clarity, enhancing cross-platform connection stability, and implementing calibration protocols validated against high-precision references.

6 Discussion

The Balance Toolkit was developed from a simple observation: posturography researchers and developers kept solving the same infrastructure problems independently, arriving at incompatible solutions that served neither community well. Our co-design process identified that both groups require reliable cross-platform connectivity, low-latency streaming, and extensible data pipelines. The differences lie not in fundamental infrastructure needs but in how that infrastructure gets applied. Clinical researchers need validated protocols and reproducible analysis, and game developers need game engine integration and real-time feedback. These are different uses of the same underlying capabilities, and designing for their intersection rather than either extreme is what distinguishes this work from previous WBB software.

6.1 Technical Performance Enables Interactive Applications

Backend and transport latencies below 0.5 ms indicate that the toolkit adds virtually no delay to the data pipeline. Although frontend latency ranges from 5.92 to 12.71 ms across platforms and represents the primary source of delay, it still falls well within the 20 to 50 ms responsiveness thresholds established for interactive systems [39, 60]. This supports P3's observation that the toolkit could enable VR locomotion driven by naturalistic body input, and more broadly demonstrates that the WBB, long dismissed as a consumer toy, can serve as practical input hardware for interactive applications where responsiveness matters.

All platforms connected reliably and maintained stable sessions, with differences confined to connection speed rather than connection success. Windows offered the fastest stable connection behavior, making it the most practical platform for both laboratory deployment and game development workflows, consistent with the 96.2% Windows preference identified in our expert survey. The slower connection times on Linux and macOS reflect the additional handling required to work around Bluetooth 2.0 quirks on those platforms, but these are one-time setup costs that do not affect session stability once a connection is established. These platform differences in connection speed are important for prospective users to understand when selecting deployment environments.

6.2 Usability Remains a Barrier to Democratization

A SUS score of 77.0 indicates above-average usability, but the five usability themes reveal a consistent underlying tension where the interface was designed with expert posturography knowledge implicitly assumed. Technical terminology such as LSL, TCP, and “window size” appeared before participants achieved basic success, and the recording workflow lacked the confirmatory feedback that non-expert users depend on to build confidence. For the toolkit to genuinely democratize balance-based interaction [25, 65], it must be accessible not only to researchers who already understand posturography but to game developers who approach it as an input device.

This reframes usability not as a polish problem but as a democratization barrier. The five themes map onto a single root cause: the interface prioritizes configurability over discoverability. For expert users, this is a reasonable trade-off. For the broader community the toolkit aims to serve, it creates friction that undermines adoption. Addressing these themes through clearer entry points, persistent status indicators, and progressive disclosure of technical parameters would bring the toolkit closer to its stated goal of making balance-based interaction accessible to any developer with a $20 USD repurposed WBB.

6.3 Repurposing at Scale

The 42 million WBBs manufactured globally represent more than a compelling statistic. They constitute an existing hardware infrastructure that sits largely idle, validated against research-grade equipment at $r = 0.99$ [13, 29] and available at approximately $20 USD used. The primary barrier to their adoption has never been hardware quality but software fragmentation, precisely the infrastructure challenge that Hodges [25] identifies as the unsolved problem in democratizing interactive hardware. Platform-specific tools, abandoned projects, and closed ecosystems forced researchers and developers to repeatedly reinvent basic connectivity and processing pipelines. Our toolkit addresses this directly through a sustainability model designed to outlast any single research group’s maintenance capacity. MIT licensing, GitHub hosting, continuous integration across platforms, and comprehensive documentation of all metric formulations create the conditions for community-driven evolution rather than eventual abandonment.

This matters beyond convenience. The pattern of WBB software appearing, gaining limited adoption, and then disappearing has left researchers unable to build on one another’s work. For example, SeeSway’s discontinuation rendered dependent workflows obsolete. By treating sustainability as a design requirement rather than an afterthought, we aim to break this cycle and establish infrastructure that the balance-based interaction community can maintain and extend collectively.

6.4 Calibration as the Path to Research-Grade Adoption

P4’s decisive rejection of the toolkit on calibration grounds, and P5’s reinforcement of this concern, point to a genuine limitation that cannot be addressed through interface improvements alone. Research-grade balance assessment requires periodic recalibration against known references, and the WBB provides no native calibration workflow. This does not undermine the toolkit’s value for interactive applications, exploratory research, or educational contexts where force-plate precision is not required. For game developers, the current accuracy is more than sufficient for responsive balance-based input. However, it does constrain adoption in clinical and high-precision research settings where sensor drift and alignment validation are non-negotiable.

Developing a calibration protocol validated against laboratory-grade force plates would substantially expand the toolkit’s research applicability. Prior work has demonstrated that calibration can reduce WBB measurement errors from 2–6 mm to 0.5–2 mm [34], suggesting that hardware precision is not the fundamental barrier. Rather, it is the absence of a standardized, reproducible calibration workflow integrated into the toolkit itself. Addressing this gap would expand adoption beyond the interactive applications and game development communities the toolkit already serves, into the clinical and posturography communities that represent 65% of our survey respondents.

6.5 Opening New Directions for Balance-Based Play

Prior CHI PLAY work has repeatedly argued that bodily forces such as gravity and balance constitute a rich but under-tooled design resource for movement-based games [23, 46]. By exposing live balance signals as reusable building blocks rather than one-off prototypes, the toolkit lets designers map specific metrics to specific play affordances. Center of pressure coordinates support continuous control schemes for navigation, steering, and avatar manipulation, extending demonstrations of weight-shift VR input [15], walking-in-place locomotion from CoP centroid and rate of change [73], stance-based abstractions for active games [8], and directional weight shifts for first-person control [32]. CoP velocity and stability indices enable adaptive difficulty, real-time skill estimation, and the movement-empowerment mappings that exaggerate small bodily inputs into amplified game effects [36]. Confidence ellipse and convex hull provide per-player calibration of play zones and target sizes, supporting the kind of inclusive, body-calibrated play that adaptive exergame systems have shown to matter for fairness and accessibility [20]. Dual-board sessions and weight-asymmetry signals open asymmetric multiplayer configurations, including competitive and vertigo-style mechanics where one player's balance perturbs another's [9, 10]. Frequency-domain features make it possible to design mechanics that respond selectively to different postural control strategies rather than treating sway as a single signal.

This is, in effect, what democratizing balance-based play means at the level of game design. Affordable hardware is necessary but not sufficient, and the signals themselves also have to be legible. Existing balance-driven games and playful systems, from elderly exergames [19] to children's maze navigation and embodied math learning [44, 45, 64], have largely operated on simple thresholds or directional weight shifts because richer metrics required reverse-engineering protocols and rebuilding pipelines for each project. Exposing CoP, velocity, stability, area, and frequency features through a shared streaming interface lowers the cost of treating balance as more than an on or off lean detector and invites the design lenses that CHI PLAY scholarship has developed for jogging, gravity, and movement empowerment [23, 36, 46] to be carried into balance-based play as well.

6.6 Enabled Research Applications

The toolkit's accessibility and low cost enable research scenarios previously restricted by infrastructure barriers, for example:

Remote and unsupervised data collection. Researchers can distribute low-cost WBBs ($20 USD used) to participants for home-based balance assessment using either a laptop or the Android companion application, removing the need to ship dedicated equipment. Participants follow illustrated activity templates, and sessions are automatically recorded with timestamped events and exported as CSV, enabling longitudinal studies of fall-risk screening or rehabilitation monitoring without laboratory infrastructure.

Mobile and outdoor exergaming. The Android companion app and dual-board support enable balance-based play beyond indoor settings. Players can bring WBBs to parks or outdoor spaces, connecting to a shared phone for cooperative or competitive exergames, supporting research into how physically situated play contexts influence engagement and motor learning outcomes.

Low-resource clinical and educational settings. Schools and clinics without access to laboratory-grade force plates can use repurposed WBBs with validated activity templates (e.g., Single Leg Stance, Timed Up and Go) for standardised screening and balance training, administered by educators or physiotherapists without specialised posturography expertise.

VR locomotion without specialised hardware. VR developers can integrate weight-shifting locomotion through the toolkit's Unity sample and real-time streaming (sub-13 ms latency) without custom hardware or Bluetooth development, enabling practical investigation of balance-driven navigation effects on presence and cybersickness.

Realizing the full potential of 42 million repurposed balance boards as both clinical instruments and game controllers now depends less on infrastructure and more on the community that uses it.

6.7 Limitations

Several limitations should be considered when interpreting these findings. The co-design phase relied on a survey without follow-up interviews or workshops, limiting the depth of workflow understanding, particularly for game developers. However, recruitment targeted authors of highly cited papers at the intersection of balance, exergaming, and gamified health, resulting in many participants combining clinical and game-oriented perspectives. The usability study focused on the desktop application, which exposes the toolkit's largest configurable surface, and involved only five participants, which we treat as appropriate for a formative first-use evaluation aimed at identifying major usability issues rather than making population-level claims, following Nielsen and Landauer's seminal model of usability problem discovery [49]. The Unity and Python samples expose data through standard streaming protocols and were assessed through technical demonstration and latency characterisation rather than developer prototyping, though a dedicated evaluation with developers building playable prototypes remains an important next step. Metric validation relies on external evidence demonstrating WBB accuracy against laboratory force plates rather than independent cross-validation. A comprehensive latency budget from sensor to game engine, force plate cross-validation, and longitudinal field trials are valuable directions but beyond the scope of this infrastructure contribution, which prioritises accessibility and community adoption over hardware-level precision benchmarking.

The hardware remains a constraint. Although the WBB offers validated sensing at low cost, it is legacy hardware, and some reliability issues persist beyond what software can fully address. Individual boards may differ in battery condition, sensor wear, and Bluetooth behavior, while pairing and connection stability can also depend on the host operating system and Bluetooth adapter. Our benchmark results therefore characterize the behavior of our test boards and host platforms rather than guaranteeing identical performance for all boards in circulation. The toolkit reduces software-side barriers to access, integration, and data streaming, but it should not be interpreted as eliminating hardware-level constraints associated with repurposed devices.

Performance benchmarks were conducted on specific hardware configurations, and Bluetooth adapter quality is known to influence WBB connectivity. Results on different hardware may vary, particularly on Windows, where adapter specifications differ widely. The Linux results reflect Arch Linux with a particular kernel version, and other distributions may exhibit different connection behavior. More broadly, the long-term maintainability of the toolkit is subject to the pace of platform evolution: operating system updates, Android Bluetooth protocol changes, and shifting hardware ecosystems can render portions of the codebase obsolete with little warning, and no software abstraction fully insulates against this. This work represents a first step in an ongoing process, and we remain committed to maintaining the toolkit and supporting community contributions.

Finally, while the toolkit validates the WBB as a practical infrastructure for balance-based interaction, it does not address the hardware's inherent precision ceiling relative to laboratory force plates. For applications requiring sub-millimeter CoP accuracy or ground reaction force measurements, as P5 identified, the WBB remains a compromise regardless of software quality. The toolkit substantially lowers the barrier to balance-based interaction but does not eliminate the trade-off between cost and precision that characterizes consumer-grade sensing hardware.

6.8 Future Research Directions

Four development priorities emerge from our evaluation findings. First, the toolkit's activity template system and Unity integration provide a foundation for investigating novel balance-based game design patterns, including asymmetric multiplayer configurations using dual boards, adaptive difficulty driven by real-time stability metrics, and VR locomotion mechanics that leverage naturalistic weight shifting. A dedicated evaluation with game developers building playable prototypes on the toolkit would surface API ergonomics, integration friction, and the design patterns developers gravitate toward when balance signals become directly addressable. These directions are immediately explorable with the current toolkit and require no additional hardware.

Second, developing a research-grade calibration protocol is essential for clinical adoption. We propose multi-point weight calibration using known reference masses, spatial alignment verification, drift monitoring algorithms, and cross-validation against laboratory force plates. Key open questions include how calibration frequency affects measurement drift in home deployments, what minimal calibration complexity achieves research-grade accuracy while remaining accessible to non-experts, and whether bodyweight-based calibration can eliminate external reference requirements. A related open question is the extent to which the current secondhand WBB fleet has degraded relative to the boards used in earlier validation studies [13, 29], since prior work establishing WBB accuracy predates the current state of the hardware by roughly a decade. Empirical sensor-degradation studies across boards of varying age and use history would directly address this uncertainty.

Third, systematic community impact assessment through structured deployment partnerships, annual adoption surveys, and contribution infrastructure would provide empirical evidence of whether the toolkit successfully democratizes balance-based interaction beyond download metrics. Tracking real-world adoption patterns, domain-specific adaptations, and sustained ecosystem development would help evaluate the long-term viability of the open-source sustainability model.

7 Conclusion

Balance-based interaction occupies an unusual position in HCI where the hardware has been validated, the applications are compelling, and the demand exists across health research and game development alike. Yet the ecosystem has remained fragmented, with tools appearing and disappearing along disciplinary lines, forcing researchers and developers to repeatedly solve the same infrastructure problems. The Balance Toolkit addresses this by providing the first community-maintainable, cross-platform framework that treats balance data as both posture assessment and game input, serving both communities through shared infrastructure rather than parallel solutions.

Through co-design with 26 domain experts, we identified that posturography researchers and game developers converge on the same fundamental requirements: reliable device connectivity, low-latency streaming, extensible integration, and sustainable open-source infrastructure. The resulting toolkit delivers sub-0.5 ms backend latency across Windows, macOS, and Linux, demonstrated Unity and Python integration, an Android companion app, six activity templates based on established protocols, and dual-board support for bilateral assessment and multiplayer configurations. First-use evaluation of the desktop application with five domain specialists showed workflow completion without assistance and good, acceptable usability ($M = 77.0$, $SD = 8.2$), with Unity integration and Windows support emerging as the most valued capabilities.

This work demonstrates that democratizing balance-based interaction is fundamentally a software infrastructure problem. As an artifact contribution to HCI infrastructure research [35], the toolkit embeds knowledge spanning device connectivity, validated posturography metrics, and cross-domain integration patterns within a maintainable open-source platform. This is knowledge that neither the health nor the game development community has previously had access to through a single shared infrastructure. Forty-two million manufactured WBBs, validated at $r = 0.99$ against laboratory-grade force plates and available at approximately $20 USD used, have never been the barrier. What was missing was sustainable, open, and extensible software that treats health assessment and interactive play not as competing applications but as different expressions of the same underlying capability. By establishing this infrastructure with community contribution pathways, we provide a foundation that can evolve with the communities it serves rather than becoming another entry in the long list of abandoned WBB software.

Future work will prioritize improving interface discoverability and action feedback, developing a research-grade calibration protocol to address the primary barrier to clinical adoption, and investigating novel balance-based game designs enabled by the toolkit's Unity integration and dual-board support.

8 Open Science and Availability

The Balance Toolkit and all associated resources are publicly available under the MIT license. The toolkit is split across two repositories: the main repository contains the React and Tauri/Rust desktop implementation, Android companion application, and Python integration scripts (TCP and LSL), while a companion repository hosts pre-built binaries for Windows and Linux, the Android APK, and the Unity sample project. Documentation covering installation, device pairing, session configuration, metric formulations, and integration patterns is included in each repository. To support reuse of the requirement analysis, we include the anonymized requirements-survey dataset in the public artifact. Contributions are welcomed through issues and pull requests.

Resource	Location
Repository root	`/`
Desktop app – source code	`/source`
Android app – source code	`/android-source`
Python integration scripts	`/python`
Unity sample project	`/unity`
Windows executable	`/windows`
Android APK	`/android`
Requirements-survey dataset	`/resources`

Table 3. Balance Toolkit resources and availability.

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