Abstract—Providing aging adults with engaging, at-home balance therapy is essential to promote long-term adherence to unsupervised training and to foster independence. We developed a portable interactive balance training system that provides real-world visual cues on balance performance using wobble board tilt angles to control the speed of a robotic car platform in a three-dimensional environment. The goal of this study was to validate this mobile balance therapy system for home use across the lifespan. Twenty younger (18-39 years) and nineteen older (58-74 years) healthy adults performed balance training with and without visual feedback while standing on a wobble board instrumented with a consumer-grade inertial measurement unit (IMU) and optical motion tracking markers. Participants performed feedback trials based on either the robotic car’s movements or a commercially-available virtual game. Wobble board tilt measurements were highly correlated between IMU and optical measurement systems (R > 0.84), with high agreement in outcome metrics (ICC > 0.99) and small bias (mean <3%). Both measurement systems identified similar aging, feedback, and stance type effects including (1) altered movement control when older adults performed tilting trials with either robotic or virtual feedback compared to without feedback, (2) two-fold greater wobble board oscillations in older vs. younger adults during steady standing, (3) no difference in board oscillations during steady standing in narrow vs. wide double support, and (4) greater wobble board oscillations for single compared to double support. These findings demonstrate the feasibility of implementing goal-directed robotic balance training with mobile tracking of balance performance in home environments.

Index Terms—Aging, rehabilitation robotics, exergame, postural control, wobble board, balance training, real-time biomechanical feedback.

I. INTRODUCTION

FALL prevention programs that target postural control can alleviate the pervasive balance decline associated with aging [1], [2], thereby reducing fall risk between 25–50% [3], [4]. However, balance therapy requires consistent, long-term adherence of at least six months to be most effective [4]. This substantial training commitment surpasses the typical six-week clinical treatment period [5], and is challenging to maintain for older adults [6], [7]. Without supervision, individuals must rely primarily on intrinsic motivation for training, and compliance drops more than 50% at discharge [8]. In addition to a lack of accountability to another individual/therapist, unsupervised training often lacks evidence of recovery progress. Without this information, the individual may not appreciate the direct health benefits from training, which reduces motivation and compliance [6], [9]. To address this problem, mobile therapy instruments that convey quantitative at-home balance performance can empower individuals to make informed healthcare decisions by providing them with objective information on their training progress [10]. In addition, remote access to mobile metrics can extend supervised care without additional clinical visits to promote long-term adherence [6], [11] for more effective treatments [4].

Balance training with a multi-axial wobble board is commonly prescribed for both preventative and rehabilitative programs. Conventionally involving a series of steady standing (i.e., minimizing level board oscillations) and dynamic tilting motions [12], wobble board training improved balance in young healthy participants [13], [14], [15], people post-stroke [16], and healthy older adults [17], [18], [19]. Wobble board training is also protective for reducing future sports-related injuries [14] and improves ankle function in young adults with chronic ankle instability [20]. Despite the positive outcomes in balance performance, a universally effective wobble board training protocol remains elusive because...
studies implemented non-standardized routines with different stance types (single vs. double support), visual cues (eyes open vs. closed), and training duration. In addition, reducing stance width on a wobble board to progressively increase the challenge level throughout treatment is common [14], [15], [20]. However, narrowing base of support may not elicit an equivalent challenge progression when standing on a wobble board compared to level ground and warrants further study.

Non-standardized balance training that is customized to the individual is effective for improving postural control in older adults [18], [21], [22]. However, personalized training currently relies on an experienced therapist’s judgement to adjust the challenge level due to a lack of direct performance measures during training [23]. Home exercise programs are not usually tailored to current performance, but rather follow a pre-defined challenge progression based on time in the program. Alternatively, interactive balance therapies that use goal-directed wobble board movements as the control inputs to video games can provide progressive challenge levels tailored to individual performance. These goal-directed therapies are effective in older adults [17], [24], potentially because they require the successful interplay between anticipatory and compensatory postural adaptations, which are affected by aging [25]. These studies linked game performance to motor coordination but lacked direct evaluation of balance performance. Off-the-shelf screen-based exercise games (e.g., WiiFit) also lack valid objective measures of therapy progress [26], [27] and can be insufficiently challenging [28]. Therefore, instrumented rehabilitation devices that quantify balance performance while intrinsically motivating users are needed to guide personalized at-home treatment practices.

An instrumented wobble board with an inexpensive tilt sensor is appropriate for home use because it can detect subtle differences related to mobility impairment [29] and progressive training challenges [30]. These sensors measured greater mediolateral tilt variation and angular velocity in individuals with functional ankle instability during unilateral steady standing on a wobble board compared to a control group [29]. An instrumented wobble board also measured oscillations during steady standing reliably and in good agreement with force plate center of pressure fluctuations in young adults [31]; however, the validity of wobble board assessments in older adult balance remains unknown. Finally, aging and virtual visual feedback effects were measured with an instrumented wobble board during active balance training [24]; however, these IMU-based metrics were not validated. Developing an affordable instrument that quantifies at-home balance performance with laboratory-equivalent accuracy has great potential to provide early detection of balance decline with aging and guide training programs.

Beyond tracking performance, real-time feedback during training facilitates complex motor learning [24]; however, the type and frequency of feedback affects performance [32], [33]. For example, higher feedback frequency (i.e., every trial vs. every other trial) is more effective for complex motor skill learning and retention [32]. This learning benefit for a complex task such as balance control may be due to the external shift in attention focus that promotes automatic movement control, retention, and transfer to daily activities [34], [35]. Because feedback perspective also affects motor learning (i.e., third-person leads to more effective learning than first-person, [36]), visual physical cues may evoke different balance coordination behavior compared to virtual feedback. That is, mapping body motion to a physical object in a real environment may promote spatial awareness that improves neuromusculoskeletal balance control in activities of daily living and be more intuitive than a screen for older adults [37]. However, the effect of interactive real visual cues on balance training performance remains unknown. Further, screen-based technology has potential health consequences with excessive use including links to digital fatigue, attention deficits, and neurodegeneration [38], [39], [40], and may also affect memory recall [41]. Therefore, alternative feedback mechanisms for at-home therapy that do not rely on a screen are needed.

The purpose of this study was to evaluate an affordable ($<500) mobile balance therapy system with robotic motion control to assess its potential for evidence-based, customized at-home balance training. We tested the instrumented therapy system’s accuracy and validity for home use across the lifespan by assessing its ability to (1) alter training performance through goal-directed feedback, (2) detect balance performance during steady standing, and (3) quantify balance metrics compared to gold standards to guide targeted therapy.

II. METHODS

A. Instrumentation

1) Robotic Visual Real-Time Feedback System Design: The mobile robotic feedback system (Fig. 1) included a motion controller with an inertial measurement unit (IMU) and a miniature robotic car with a microcomputer (Table I).

Euler angles were calculated in real-time with an embedded system using the IMU signals (BNO055 9-DOF, Adafruit, New York, New York) and transmitted wirelessly to a microcomputer (Raspberry Pi 3B+, Cambridge, United Kingdom) at an unequal sampling rate (average: 40 Hz, range: 10-110 Hz).
Fig. 2. Human-in-the-loop control schematic of the robotic real-time feedback balance training system. Wobble board pitch ($\theta_P$) and roll ($\theta_R$) angles are calculated using the IMU motion-controller signals and transmitted wirelessly to the robot microcomputer. Pitch and roll angles are linearly mapped ($\beta_1=$slope, $\beta_0=$intercept) to car linear ($v$) and angular ($\omega$) velocities, respectively, and converted to motor velocity for closed-loop proportional-integral (PI) speed control of each wheel. The central nervous system perceives the robotic real-time feedback, plans, coordinates and executes movements using the neuromusculoskeletal and sensorimotor systems. Brain image courtesy of [42].

### TABLE I

| Part Type               | Wobble Board Instrumentation                  |
|-------------------------|------------------------------------------------|
| Motion Controller       | Adafruit BNO055 9-DOF Breakout                 |
| Microcontroller         | Adafruit ItsyBitsy (Atmega32u4, 5V, 16MHz)     |
| Transceiver             | NRF24L01 wireless (1.9-3.6V, 2.4GHz)           |
| Battery (MCU)           | Adafruit lithium ion polymer (3.7V, 150mA)     |

| Robot Platform          | Pololu Zumo 32U4 Robot Kit                    |
|-------------------------|------------------------------------------------|
| Motors                  | 75:1 Micro Metal Gearmotor HPCB (6V)           |
| Car batteries           | Rechargeable NiMH AA (1.2 V, 2200 mAh)        |
| Transceiver             | NRF24L01 wireless (1.9-3.6V, 2.4GHz)          |
| Microcomputer           | Raspberry Pi 3 Model B+                       |
| Battery                 | Li-Polymer battery HAT for Raspberry Pi       |

The microcomputer performed data acquisition and high-level processing, which involved mapping the IMU angles (pitch/roll) to car velocity (linear/angular) for robot control. Pitch and roll angles were chosen because they characterize standard wobble board therapy [12]. The robotic platform included a robot kit (Zumo 32U4, Pololu, Las Vegas, Nevada) and dual motor drive system (quadrature encoders, 12 counts/rev) for closed-loop proportional-integral speed control of each wheel. This human-in-the-loop robotic system (Fig. 2) connects intrinsic body control to extrinsic robotic car movements in a physical maze, while storing IMU-based tilt angle measurements for balance performance evaluation.

2) **Virtual Visual Real-Time Feedback System**: The commercially available screen-based balance training system (Sensbalance Miniboard Wireless, Sensamove, Groessen, Netherlands) included a motion controller that mapped wobble board tilting to on-screen maze movements (Fig. 3). This system served as a clinically relevant comparison to the robotic feedback system, with improved balance and therapy engagement reported in older adults [17], [18], [24] and functional balance reported in individuals post-stroke [43].

3) **Wobble Board & Optical Motion Capture Systems**: A commercially-available wobble board (Wobblesmart, Wobblesmart International, Denmark, Europe) was set to level one (i.e., most stable setting) for all trials to eliminate the effect of geometric board variations (Fig. 4). This setting provided approximately 15 degrees of multi-axial tilt with a half-round adjustable pivot (diameter=14 cm, height=6.5 cm, [44]).

Four retroreflective spherical markers (14-mm diameter) were placed on the wobble board’s standing platform (diameter=39 cm) and were tracked at a sampling rate of 150 Hz (n=2) or 200 Hz (n=37) with a seven-camera.
optical motion capture system (OQUS 300+, Qualisys AB, Gothenburg, Sweden). Optical motion capture affords sub-millimeter position tracking accuracy in a fixed reference frame [45] and therefore serves as a gold-standard comparison. For tracking the wobble board pose, the origin was defined as the midpoint between the left and right reflective markers in a positive forward-left-up convention. A distal landmark was defined in a calibration trial at the projection from the origin to the point of contact with the floor (Visual3D, C-Motion, Inc, Germantown, MD). This landmark was then defined relative to the tracking markers for all subsequent trials. The IMU-based motion controller and virtual feedback sensor were aligned to the wobble board’s coordinate system and secured to its surface (Fig. 4).

B. Participants
A convenience sample of healthy younger (n=20, 18-39 years) and older (n=19, 58-74 years) adults volunteered to participate in this study (Tables II,III). Participants self-reported limb dominance as the leg they preferred to kick a ball. All participants had active lifestyles, performing moderately strenuous physical activity (e.g., brisk walking, running, sports) at least three times per week. No participants were professional athletes or presently training in balance-specific sports (e.g., gymnastics, ballet). They were free from cognitive, neurological, vestibular, visual, or musculoskeletal impairment that could affect study measurements by self-report. In the past six months, none of the participants had experienced an injury or fall with a wobbleboard. All participants provided their written informed consent prior to starting the study procedures, which were approved by the Colorado Multiple Institutional Review Board (Protocol 21-2971).

C. Experimental Protocol
Participants completed wobble board balance training without real-time visual feedback and were randomly assigned to also perform training with either robotic or virtual feedback. The conventional wobble board training approach without real-time feedback involved (1) controlled forward/backward and side-to-side tilting maneuvers while avoiding touching the board’s edge to the floor, and (2) steady standing with the board horizontal [12]. Participants focused their gaze on an X marked on the floor 1-m away from their base of support during trials without feedback. Data were simultaneously collected for each trial with optical and IMU-based systems. Two handrails were secured to the floor on either side of the participant to mitigate fall risk; however, participants were encouraged to perform the tests with arms out to their sides. A standard arm position was not enforced to improve comfort level during testing. All trials were performed unshod with or without socks according to participant preference.

1) Dynamic Balance Training: For the tilting trials without real-time visual feedback (No Feedback), participants performed two repeated 40-second trials per direction (forward/backward and side-to-side) while standing in narrow double support with the medial borders of their feet touching. Participants then performed seven minutes of structured practice either driving the robot or moving the ball with board tilting motion (Feedback). Next, they navigated the robot/ball through a real (Fig. 1) or virtual (Fig. 3) maze as far as possible during three repeated one-minute trials (Fig. 5). Participants inherently received performance feedback based on their ability to progress the robot/ball toward the goal. Also, all participants were given similar verbal encouragement between trials, which was unrelated to their individual performance.

2) Steady Standing: For the steady standing trials, the goal was to minimize wobble board oscillations while keeping the board horizontal. Participants performed two (older group) or three (younger group) repeated 40-second trials in three
standing positions in random order (Fig. 6): (a) wide double support with feet hip distance apart and self-selected toe-out angle, (b) narrow double support with medial borders of feet touching, and (c) single support on the non-dominant leg. Participants centered their stance on the wobble board, with their toes in-line with the board’s anterior/posterior markers. Tape was placed on the board marking the distal foot locations to achieve consistent positions across trials.

D. Data Analysis

The optical and IMU-based trajectories were low-pass filtered with a bidirectional 8th-order Butterworth filter ($f_c = 6$ Hz and 8 Hz, respectively). Optical pitch (sagittal plane rotation) and roll (frontal plane rotation) angles were calculated using the x-y-z Cardan sequence (+x anterior, +y left, +z up, Fig. 4) and downsampled to 50 Hz with a decimation low-pass 13th-order Chebyshev filter. IMU-based angles were linearly interpolated to 50 Hz. Angles from both systems were zero-meaned and then time synchronized by cross-correlation (Fig. 7).

Wobble board angular velocities were calculated by frame-to-frame changes in board orientation. We first calculated the discrete rotation matrix between subsequent time points ($A$, $B$) in the laboratory reference frame ($O$) as

$$R_{AB} = R^T_{DA} R_{OB}.$$ 

Then, we performed the log map from $R_{AB}$ to the equivalent axis-angle rotation based on Euler’s theorem [46]. This discrete axis-angle rotation vector was then divided by the time step to estimate angular velocity.

E. Statistical Analysis

We compared the optical and IMU-based motion capture systems’ quantification of balance performance outcome metrics across feedback type, stance type, and aging groups. All outcome metrics were calculated across a 30-second duration. Angular path length was the sum of Euclidean distance (in degrees) between successive samples of wobble board pitch and roll angles (Fig. 7b). Mean absolute velocities were also calculated as the average of the absolute value of individual pitch and roll components of angular velocity in the laboratory reference frame.

We performed linear mixed effects analysis with R (R Core Team, 2021, v4.1.2) and lme4 [47] to assess the relationship between outcome metric and dynamic tilting balance training with feedback type (no feedback, robotic or virtual real-time feedback) and age group (older, younger) as fixed effects. Participant intercepts were the random effects with feedback types as the nested factor. Similar mixed effects models were performed for the steady standing tasks with age group and stance type (wide double support, narrow double support, single support) as fixed effects and stance types as the nested factor. Visual inspection of residual plots supported homoscedasticity and normality assumptions. Estimated (i.e., least-square) marginal means and model differences were used to calculate the percent differences between age groups, stance types, and feedback.

We quantified Pearson correlation coefficients of the time-matched, zero-meaned signals to assess the correlation between wobble board angles and angular velocities measured with the optical and IMU-based systems during steady standing and tilting movements with and without real-time feedback in younger and older adults. We also performed Bland-Altman analyses [48] and calculated Intraclass Correlation Coefficients (ICC) to study the agreement between the optical and IMU-based outcome metrics.

III. RESULTS

A. Dynamic Balance Training: Feedback Effects

Without real-time feedback, the older group performed greater angular path lengths (35-54%, Fig. 8) and faster mean absolute velocities (pitch: 29-52%, Fig. 9; roll: 42-60% Fig. 10) compared to the younger participants ($p<0.05$). However, when older participants performed robot or virtual feedback, their angular path lengths and mean angular velocities decreased to similar levels as the younger cohort ($p>0.1$, Tables S1-S2). The IMU and optical motion capture systems detected similar differences in balance training performance related to aging and feedback (within 2% difference across metrics).

B. Steady Standing: Screening Tool

During steady wobble board standing, the IMU and optical motion capture systems revealed similar aging and stance
Fig. 8. Angular path length for dynamic tilting trials box and whisker plots (line=median, box=first quartile, whisker=third quartile, dots=outlying points) [49]. The older participants performed greater angular path lengths across 30-second isolated tilting trials without real-time feedback (No Feedback) compared to the younger cohort (p<0.05). With either robot or virtual real-time feedback (Feedback), the older participants performed smaller angular path lengths (p<0.05), which were similar to the younger participants (p>0.1). The IMU and optical motion capture systems measured similar aging and feedback effects.

C. IMU System Accuracy

Across all trials, the optical motion capture and IMU-based time-matched signals were highly correlated, indicated by Pearson correlation coefficients (mean ± SD) of 0.98 ± 0.05 and 0.84 ± 0.1 for the wobble board angles and angular velocities, respectively. Intraclass Correlation Coefficients (ICC>0.99, p<0.0001), Bland-Altman biases (<3%) and limits of agreement (Fig. 12) revealed excellent agreement between the optical and IMU-based outcome metrics. The outcome metric comparisons included 77% of all trials due to intermittent signal dropouts (∆t>0.5 s) from radio transceiver interference.

IV. DISCUSSION

Effective balance therapy requires long-term adherence to a customized training program. However, compliance to unsupervised training is challenging, especially if the training is insufficiently challenging and the health benefits are unclear. Interactive mobile therapy instruments can motivate participation in home training programs through real-time feedback and remote monitoring of recovery progress by storing performance metrics (e.g., angular path lengths and velocities) over the course of a training session. These balance scores could automatically be uploaded to a mobile device and shared with a clinician to extend supervised training. Understanding how feedback type and narrowing base of support affect wobble board balance training in aging adults provides valuable insights towards tailoring therapy programs for more effective treatments. Therefore, this study validated the performance of a portable, interactive balance therapy system with hands-free robotic feedback by comparing it to an established virtual feedback system and testing agreement with lab-based measurements.

A. Dynamic Balance Training: Feedback Effects

The older adults performed isolated dynamic tilting trials without real-time visual feedback with potentially more difficulty controlling rotation compared to younger adults,
as measured by greater angular path lengths and faster angular velocities. The older cohort may have chosen to avoid slower movements without feedback because the transition between dynamic and static states is more challenging [50], [51], and potentially more prevalent at slower speeds. The addition of goal-directed feedback encouraged the older participants to perform slower, more controlled tilting motions, which were similar to the younger adults. This immediate change in active movement suggests that older adults have the capacity to alter balance training performance through goal-directed feedback training, similar to prior study [24]. However, additional research is necessary to establish the relationship between board tilting movements and improved dynamic balance control. Additional benefits may also be realized because this training approach combines anticipatory (i.e., route planning) and compensatory (i.e., balance correcting) postural adjustments, which are affected by aging [25]. Through real-time feedback balance training, older adults can learn to effectively initiate movements using anticipatory and volitional control, which can reduce the magnitudes of compensatory postural adjustments [25], [52]. Further, cognitive engagement with balance training can stimulate neuroplasticity for improved balance recovery [53]. Therefore, goal-directed feedback balance therapy has great potential to promote immediate and long-term balance control in older adults.

Providing robotic visual real-time feedback to older adults affected their training performance in a similar capacity as a commercially-available, clinically-relevant virtual feedback system with established efficacy in older adults [17], [18], [43].

This comparable outcome was achieved using the common goal to move the robot/ball as far as possible, despite subtle controller differences between systems. The robot also provides interactive balance therapy without the use of a screen. Therefore, performing this alternative therapy in a home setting will not contribute to the increasing detrimental effects of digital fatigue [54]. Translating the current system for home use would require a mobile device application that provides seamless operation, training outcome assessments, and data uploading capabilities. In a home setting where handrails may be unavailable, a doorway, furniture, or counter edge can be used to ensure safety. Also, a specific track may not be needed in the home, but rather any course could be established using everyday objects as obstacles and/or following longer paths.

Whereas this study revealed similar dynamic balance training performance between the two feedback systems, further research is required to establish how feedback affects the underlying biomechanics during balance training. Specifically, subtle differences in muscular demand and kinematic strategies may exist between virtual and robotic feedback, and these effects may differ across the lifespan. In addition, this experiment was controlled to a subset of challenges for all users. The highly variable response to feedback across users suggests benefits may exist from tailoring the initial challenge level to balance skill. For example, a more uniform response across users may be realized by incorporating the spectrum of available games, controller modes, and wobble board levels. Therefore, further study is needed to assess the full potential of each system and to guide progressively demanding therapy.
The older participants performed higher mean absolute roll velocity during isolated tilting trials without real-time feedback (No Feedback), which may indicate more difficulty controlling frontal plane rotation compared to the younger group ($p < 0.05$). With either robot or virtual feedback (Feedback), the older group slowed their roll velocity ($p < 0.05$) to similar levels as the younger participants ($p > 0.1$). The IMU and optical motion capture systems demonstrated similar aging and feedback effects.

B. Steady Standing: Screening Tool

During steady standing, healthy aging produced detectable changes in IMU-based wobble board signals. The 50% higher and faster board oscillations for the older adults compared to the younger group across stance types is consistent with prior study of aging effects on level ground quiet standing [55], [56]. Center of pressure velocity during level ground quiet standing as measured in Era et al. is well-established as a surrogate for balance control, with higher velocities related to recurrent falls [57], [58]. Therefore, the comparable aging effect found in this study indicates that an affordable instrumented wobble board can also be an effective screening tool for detecting reduced balance control associated with healthy aging. Because defining balance ability requires more than a single test [59], combining these steady standing assessments with the voluntary dynamic training performance metrics could further elucidate aging-induced balance deficits. Future research to assess if wobble board balance metrics can predict fall risk is warranted.

Double support steady standing elicited similar balance performance for the older adults compared to single support wobble board balance in the younger adults (9–24% difference across metrics, $p > 0.25$), which provides perspective on the relative task demand for each group. That is, the muscular demand may be similar for older adults in double support as younger adults in single support on a wobble board, just as increasing balance task demand by reducing the radius of the half-round adjustable pivot corresponds to greater center of pressure path lengths, muscle activity, and co-activation [44]. However, further research on muscle demand during steady wobble board standing in older adults is required because aging likely elicits additional compensations. These findings serve as a comparative tool to guide periodic at-home assessments for early detection of balance deficits with healthy aging and monitoring training efficacy.

Reduced balance control due to narrowing base of support to a single leg during steady standing was also detected by the IMU-based wobble board metrics, with an increase of 45% for both age groups. Surprisingly, narrowing double support from hip width to feet touching did not increase the wobble board oscillations, which implies similar whole body balance control is required for both tasks. This finding contrasts the increase in postural sway that occurs with narrowing double support during level ground quiet standing [60] and implies that narrowing double support stance width on a wobble board does not progress the task demand as it does on level ground. However, underlying muscle contributions may be affected by stance width and not reflected by wobble board kinematics. The presented results suggest that when used as a screening tool, wide or narrow double support stance widths can be used interchangeably. Therefore, individuals can self-select a comfortable stance width, which may improve balance...
Fig. 11. Steady standing outcome metrics (angular path length and mean absolute angular velocities across 30 seconds) were similar when measured by optical motion capture or IMU-based systems (<3% difference). Wobble board oscillations were greater for older compared to younger adults across stance types (p<0.01). Single support stance elicited greater board oscillations compared to both double support stances across age groups (p<0.01).

Fig. 12. Outcome metrics (angular path length, mean absolute pitch/roll velocity) measured with the IMU and optical motion capture systems indicate high agreement between systems: (top row) scatter plots with Intraclass Correlation Coefficients (p<0.0001) and (bottom row) Bland-Altman difference plots (IMU-Optical) with mean bias (red) and limits of agreement (2 standard deviations from mean).

confidence. Also, these findings can facilitate screenings and research designs by potentially allowing balance assessments to be conducted without standardizing stance width across trials. Further research is needed to confirm these findings for different wobble board levels, and to test whether the results are similar in people with impairments or greater fall risk.

C. IMU System Accuracy

The IMU-based system provided accurate wobble board tilt angles and angular velocities with similar measurements compared to the optical motion capture system (R>0.84). The two systems also demonstrated excellent agreement in outcome metrics during steady standing and active tilting motions, with Intraclass Correlation Coefficients that were greater than 0.99 and mean system bias that was less than 3%. The IMU and optical systems’ outcome metric Intraclass correlations were higher (+0.23 across metrics) than previously reported correlations between IMU and force plate center of pressure mean velocities [31], which is likely because both systems in this study directly measured wobble board tilt angle. The small negative bias indicates that the IMU slightly underestimated tilt angle compared to the optical measurements, likely influenced by intermittent signal dropout from radio transceiver interference. Collecting the IMU signal at a consistently higher sampling rate (>10 Hz) with a more robust communication protocol (e.g., Bluetooth) could mitigate this bias. Despite signal dropouts (Δt<0.5 s), the IMU-based system demonstrated similar ability to detect differences in balance associated with aging, feedback type, and narrowing base of support. In addition, robot speed was maintained until the next available IMU command; therefore, the dropped signals were imperceptible to the user.
V. CONCLUSION
A wobble board instrumented with a consumer-grade IMU provides valid assessments of balance performance during steady standing and dynamic tilting movements. Healthy older adults adapted their balance training performance to levels comparable to younger adults when using either robotic or virtual real-time feedback. Therefore, an affordable robotic system has great potential to provide engaging, evidence-based balance training for aging adults in a home environment.

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