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Sensor-based Approach for Objective Balance Skill Assessment: A Review

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Review Article

Abstract:
This paper provides a review of sensor-based platforms utilized in the assessment of balance skills, offering insights into various types of sensors, outcome measures and efforts in clinical evaluations. Balance skill assessment is crucial in understanding and managing various neuromuscular disorders, injuries, and age-related declines in motor function. The review categorizes sensor-based platforms into a few main types such as wearable sensors, force plates, and accelerometers. The paper addresses the benefits and drawbacks of each type of sensor as well as the corresponding outcome measures for each sensor. Outcome measurements include sway velocity, center of pressure excursions, and temporal-spatial movement features. Sensor-based platforms have been shown in clinical tests to have the potential to detect small changes in balance that may not be detected using conventional assessment methods. The review provides evidence for the effectiveness of sensor-based assessments in a range of clinical populations, such as older people who are at risk of falls, those with musculoskeletal injuries, and neurological illnesses. Moreover, a comparison with traditional ways of evaluating balance clarifies the benefits of sensor-based platforms, such as higher sensitivity, objectivity, and the capacity to record dynamic aspects of balance. This paper offers practitioners, physicians and researchers some useful insights for evaluating and rehabilitating patients with balance-related impairments. Sensor-based measures for more individualized training feedbacks, promoting optimal outcomes in balance training and rehabilitation, are also presented.
Keywords: Objective balance test; Sensor-based; Wearables; Force plate; Accelerometer

1. INTRODUCTION

As countries worldwide experience a demographic shift towards an aging population, the implications of balance and postural control become paramount (1). An estimated 35% of individuals aged 65 and over fall each year, with falls accounting for 40% of all injury-related deaths (2). Approximately 30-51% of falls in hospitals result in some form of injury, ranging from minor bruises to severe wounds and fractures. Falls are associated with a longer length of stay in hospital, greater utilization of healthcare and higher rates of discharge to nursing homes and this leads to a financial burden. Beyond these alarming statistics, even non-fatal falls can lead to a "post-fall syndrome," a condition marked by psychological, postural, and gait dysfunction, particularly in the elderly (3). This emerging public health concern has generated substantial economic burden, necessitating the development of effective preventative measures (4).

Historically, balance has been central to human health, enabling effective movement, maintaining upright orientation, and responding to environmental challenges. Balance impairments, especially in older populations, have direct repercussions on quality of life, well-being, and fall risks (5). Furthermore, the occurrence of near falls, resulting from slips or stumbles but avoided due to corrective actions, often go unnoticed but are significant predictors of actual falls (3). Balance focuses on maintaining the center of gravity within the base of support. Postural control encompasses overall body stability and orientation, including both balance and the coordination of body segments.

Traditional balance assessment methods, such as posturography through force platforms and optoelectronic systems, have their limitations (6). Though they are sensitive and objective, they often need simulated conditions under the supervision of professionals for the assessment (1). Conversely, the last decade and a half has seen a surge in wearable sensor technology, especially inertial sensors (7). These wearable devices hold promise for their affordability, portability, and applicability in real-world settings, permitting the objective evaluation of balance and gait in everyday environments (1).

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Wearable sensors show promise in differentiating age groups and identifying neurological disorders like Parkinson’s disease and multiple sclerosis (8). However, their reliability and validity need to be firmly established, particularly in populations prone to falls (9). Despite the transformative potential of these sensors for unobtrusive analysis of motor behavior outside laboratories, there is a lack of comprehensive literature on their use in balance assessment (1, 10).

While technological advancements offer the possibility of revolutionizing early detection and intervention for balance impairments (11), further research is needed to explore the full range of applications for wearable sensors in this context (12). Given this backdrop, this review seeks to delve into the current literature on the validity and reliability of sensor-based methods for assessing balance assessment (13). We aim to uncover the potential and challenges sensor-based balance assessment tool present in balance assessment, emphasizing their application among different populations (14, 15). This review examines sensor-based methods for assessing postural sway and other balance measurements, emphasizing validity and reliability. Distinct from existing studies, the focus here is on the integration of technology in diverse environments and its impact across various populations. The potential and challenges of these tools in balance assessment are identified and discussed.

2. METHODOLOGY

In this review, the focus was on studies that sensor-based technologies for balance assessment. The goal was to comprehensively understand these methods, including their benefits, limitations, and applications in clinical and athletic settings. Specific search terms used included 'sensor-based balance assessment', 'balance technology', 'wearable sensors for balance', along with terms like 'inertial measurement units' and 'pressure mats'. The search spanned several databases including Google Scholar, PubMed, ScienceDirect, and Scopus, targeting publications from 2010 to the present to capture the most recent advancements.

Study Period: The review targeted publications from January 2010 to December 2023, ensuring the inclusion of the most recent advancements and findings in the field.

Inclusion Criteria: Studies included were those published in English, presenting original research on sensor-based balance assessment for healthcare or sports applications. The studies needed to provide empirical data on the effectiveness, validity, or reliability of the assessment methods.

Exclusion Criteria: Excluded were studies that focused solely on theoretical analyses, vestibular evaluations without direct implications for sensor-based assessment, or biomechanical analyses not applied to practical balance assessment. Commentaries and editorials were excluded.

Initially, the search yielded approximately 106 studies. To ensure the inclusion of the most relevant research, titles and summaries of each study were scrutinized. This screening process was conducted by two independent reviewers, with a third reviewer available to resolve any discrepancies. After thorough screening, 59 studies met the inclusion criteria and were included for detailed analysis.

From these studies, key information such as authors, publication year, methodology, population studied, and findings regarding the validity, reliability, and limitations of the methods was extracted and analyzed. This facilitated a clear synthesis of the significant advancements and findings in the field of sensor-based balance assessment technologies.
The review highlighted a growing interest in leveraging technology for deeper insights into balance, showcasing how these innovative methods offer precise, detailed, and swift data. Despite the promising outcomes, integrating these technologies into routine practice poses challenges. This paper also details the development and clinical application of sensor-based devices for balance assessment, emphasizing their importance in enhancing our understanding and capabilities in this domain.

3. SENSOR-BASED DEVICES FOR BALANCE ASSESSMENT

Sensor-based method typically involves tracking a patient's postural sway and movement patterns using wearable sensors, such as accelerometers, gyroscopes, and pressure sensors (16). To collect data in real-time, these sensors can be affixed to the patient's body or incorporated into the surrounding area. Comparing this method to traditional balance assessment testing has various benefits. As the data gathered is measurable and can be analysed using computers to create relevant metrics, it firstly offers a more objective assessment of balance (17) . The ability to continuously monitor patients enables a more thorough evaluation of their balance over time. Finally, sensor-based method is suitable in a decentralized setting, including the patient's home, a clinic, or a community centre, and is non-invasive, enabling patients to walk around freely.

FIBOD: This is a sensor-based balance board, with the option of a round foam sponge support at the base. To use it, the user must stand on the balance board and maintain balance for a set time, typically 10 seconds. The sensors on the board capture motion data, feeding it into an assessment algorithm to provide instant feedback. This includes balance scores and biofeedback, serving both as motivation and a tracking mechanism for standing balance progress. The system incorporates visual feedback via TV, alongside a timer and animated instructions to guide users. Compatibility with Android-based devices like phones and TVs ensures versatile usage. The subject stands on the FIBOD, with feet apart at shoulder width, hands at the sides, and focuses on a point on the TV. Before starting, the subject is allowed to familiarize themselves with FIBOD, and there is a rest period between different balance test trials. The test can be conducted several times, with eyes both open and closed (18). FIBOD is suited for static and dynamic balance test. However, there were not many studies and norm data available based on FIBOD.

Biodex Balance System SD: The Biodex Balance System SD is a dynamic balance testing and training tool. It offers a variety of balance tests and training settings, as well as real-time feedback on an interactive touch screen display (19). The balance platform adapts to different levels of instability on several different planes, challenging users and promoting balance development (20). This approach is frequently used in conjunction with conventional clinical tests like the Timed

Up and Go test and the Berg Balance Scale to provide a more thorough and objective evaluation of postural control and stability (21). It is especially helpful for finding balance deficiencies in groups like the elderly or people undergoing physical therapy (22). Biodex has been used in hospital settings and has published norm data. Nevertheless, it is heavier (89kg), less portable and more expensive compared to a conventional wobble board.

NeuroCom Balance Master: Designed to unbiasedly evaluate and enhance balance, the NeuroCom Balance Master is a comprehensive computerized posturography device (23). It accurately measures changes in postural control and center of gravity under a variety of circumstances using force plate technology. This device can assess balance while performing both static and dynamic tasks, such as shifting one's weight, moving, and testing one's stability limit (24, 25). Clinical tests like the Clinical Test of Sensory Integration of Balance and the Romberg Test are frequently supplemented by it, giving clinicians precise quantitative data that might aid in creating individualized treatment regimens (26). Similarly to the Biodex system, it can be expensive and requires trained personnel. The space required for installation could also be a limitation for some facilities.

The VertiGuard® RT system measures a user's reactions to disturbances by using a mix of body-worn accelerometers and gyroscopes. This offers factual information on a variety of balance-related topics, such as postural sway, postural reactions, and sensory integration (27). The software for the system also includes a number of workouts and assessments that enable a thorough evaluation of balance and sensory integration (28). This system's specificity and ability to measure balance under particular conditions could limit its application to a broader range of scenarios (29).

Wii Balance Board: Originally intended as a gaming accessory, the Wii Balance Board has been proven to be a legitimate and trustworthy instrument for balance testing in clinical and research contexts. Through the use of pressure sensors, it measures the user's center of balance and weight changes. This tool can be used in conjunction with conventional tests like the Berg Balance Scale and provides a cost-effective alternative to more expensive balance systems (30). Due to its interactive features, balance training sessions might increase patient involvement (31). While accessible and affordable, it is less precise than medical-grade equipment. It was not originally intended for medical use, and its durability and longevity are often questioned (32).

Proprio 5000: To evaluate and train balance, the Proprio 5000 combines force plate technology and infrared sensors. Weight shifts and postural control are measured by the apparatus, which provides objective data that may be compared to normative values or recorded over time to track development (33). Its gamified methodology makes balance training interesting and pleasurable, boosting user motivation and programme adherence (34). Its sophisticated six-degrees-of-freedom movement testing is overwhelming for some users (35), especially older adults.

Korebalance: The Korebalance system tracks the user's changes in centre of gravity using sensors on a pressure-sensitive platform. The platform's movements put the user's balance to the test, and the sensors provide them precise feedback on how they did (36). Korebalance is a flexible instrument for both evaluation and rehabilitation since it offers a wide variety of exercises and activities for balance training in addition to balance testing (37). The interactive aspect of this device could be distracting or confusing for some users. Again, the cost could be a limitation for some facilities (38).

Balance Tracking System (BTrackS): BTrackS measures the forces generated by the feet using a force plate with integrated sensors, providing comprehensive information about the user's balance. Additionally, this device has software that analyses the data and generates measurements of balance and postural control that are objective (39, 40). A highly accurate and dependable approach for assessing balance is provided by the BTrackS Balance Plate, which is helpful for locating balance deficits and monitoring the development of rehabilitation (41). This system provides basic force plate technology, but it may not offer the full range of testing and interactive training options that some other systems provide (42).

APDM Wearable Technologies: The Opal sensors, which are small wearable devices featuring tri-axial gyroscopes, accelerometers, and magnetometers, are used by APDM's Mobility Lab for this balancing evaluation system. These sensors record information about the user's motions and analyse it to generate balancing measurements (43, 44). APDM Mobility Lab not only replaces conventional techniques like the Timed Up and Go test and Berg Balance Scale, but it can also offer new insights into more intricate facets of balance, like anticipatory postural modifications and postural reaction to disturbances (45).

HUR Balance Platforms: The HUR Balance Platforms feature integrated software that makes balance training and testing easier. The platforms give quick input on changes in center of gravity and weight distribution, enabling a thorough evaluation of a person's balance (46). Additionally, the platforms have exciting game-based training programmes that make learning balance easier for users (47). They not only offer a useful tool for measuring progress in balance training programmes and for adjusting those programmes to the individual's particular needs, but they can also supplement conventional balance examinations like the Balance Error Scoring System (48).The system lacks the versatility of some other balance assessment systems, and its reliability dependents on the user's ability to perform the tests correctly.

The TekscanMobileMat collects information on pressure distribution and the movement of the center of pressure using embedded pressure sensors spread out across the mat. As a result, it can give very particular and in-depth information about the user's stability and balance (49). The system's software also offers a number of exercises and assessments that can be tailored to the user's particular requirements, making it a flexible tool for training and assessing balance (50). While this is a portable option, it might not offer the same accuracy as larger, stationary systems. It measures pressure distribution but might lack the ability to provide comprehensive balance and postural stability metrics (51). Below is a list of sensor-based devices summarized in Table 1. The type of sensors used and the conventional assessments that these devices can alternatively replace, is also mentioned.

Table 1. Sensor-based devices for balance assessment

Name of Devices	Sensors Type and Placement	Aim	Sampling Frequency	Performance metrics	Limitations
FIBOD (18)	Accelerometers, gyroscopes.	To access and improve balance.	20 Hz.	Anterior-posterior stability index (APSI), medial-lateral stability index (MLSI), sverall stability index (OSI), Sway velocity and zone ratio.	Primarily focuses on static and dynamic balance and lacks norm data for comparison.
Biodex Balance System SD (18)	Pressure-sensitive platform with multi-axial movement detection.	To assess and improve balance, stability, and postural control, providing valuable data for rehabilitation and fall risk assessment.	20 Hz.	Biodex stability index (BSI) and limits of stability (LOS).	Primarily focuses on basic functional tasks, may not capture subtle balance deficits.
NeuroCom Balance Master (52)	Force plate sensors placed on the floor.	Assess static and dynamic balance through different type of tests.	Approximately 100 Hz.	Speed of oscillation of the center of pressure.	Has limitations in assessing balance during other directions of movement.
VertiGuard® RT System (53)	Wearable sensors (accelerometers, gyroscopes).	Real-time observation and evaluation of postural stability and control.	Approximately 100 Hz.	Mean velocity of sway.	Limitations in capturing specific balance deficits.
Wii Balance Board.	Pressure sensors placed in the four corners of the board.	detect changes in balance and movement during game play.	Approximately 100 Hz.	Center of pressure (COP) trajectory to derive features like total path length, medio-lateral and antero-posterior path length, range and sway speed, area of the 95% confidence ellipse (30).	Limited in capturing postural stability during static tasks.
Proprio 5000 (54)	Pressure-sensitive mat sensors.	Offers a thorough evaluation of balance and mobility for the prevention and rehabilitation of injuries.	50 - 100 Hz.	Composite balance, somatosensory ratio, visual ratio, and vestibular ratio.	Limitations in capturing dynamic balance and mobility balance.
Korebalance (38)	Pressure-sensitive platform sensors.	Improve strength, balance, and coordination for athletic performance or rehabilitation.	50 - 100 Hz.	Dynamic motion analysis score.	Limitations in assessing dynamic balance.
Balance Tracking System (BTrackS) (40, 41)	Force plate sensors.	Assessment of balance and fall risk in vulnerable populations, such as the elderly and people with neurological problems.	100 Hz.	Center of pressure and Level of Service Area.	Limitations in assessing dynamic balance during complex movements.
APDM Wearable Technologies	Wearable inertial sensors.	Gathering and analysing mobility data for academic and therapeutic purposes.	10 - 128 Hz.	Gait and Balance Analysis, Kinematic measurements (44).	Limitations in capturing dynamic balance.

Name of Devices	Sensors Type and Placement	Aim	Sampling Frequency	Performance metrics	Limitations
HUR Balance Platforms	Pressure-sensitive platform sensors.	To evaluate balance and stability for rehabilitation and fitness training.	50 - 100 Hz.	Anthropometric measures and postural stability assessment (47)	Limitations in capturing dynamic balance, not suitable for individuals with conditions other than stroke.

4. CLINICAL STUDIES WITH SENSOR BASED BALANCE ASSESSMENT DEVICES

Sensor-based balance assessments differ primarily from conventional practices in their data collection methods and approaches. Table 2 compares sensor-based and conventional balance assessment evaluations, utilizing technology devices like force plates, gyroscopes, and accelerometers to measure and quantify various elements of body movements and postural stability in a more detailed and quantitative manner. The analysis highlights the potential of combining sensor-based and conventional methodologies for a better understanding of a person's balance (55). This study emphasizes the lack of available data on posturographic variable calculation techniques for identifying older adults at high risk of falling, underscoring the need for future research to pay more attention to methodological specifics and standardization to enhance reproducibility.

Table 2. Studies comparing sensor based and conventional balance assessment

Research Titles	Measurement Tools	Outcome Measure	Analysis	Key Findings
Validity of using wearable inertial sensors for assessing the dynamics of standing balance (55).	Berg Balance Scale Two-minute standing test on a force-plate	Risk of fall	RMSE (root-mean square error) Correlation coefficient ANOVA	High correlation between balance assessments of wearable inertial sensors and traditional clinical measures. The drawbacks are the need for sensor calibration and data variability due to sensor positioning.
Evaluation of the Tinetti score and fall risk assessment via accelerometry-based movement analysis (56).	Wearable accelerometer Tinetti clinical scale	Risk of fall	Correlation analysis	Accelerometers provide higher predictive accuracy for fall risk compared to the Tinetti score alone and can identify more subtle movement patterns associated with increased fall risk.
Examining the reliability, correlation, and validity of commonly used assessment tools to measure balance (57).	Biodex Balance System SD Timed-up-and-go (TUG) Four-square step test (FSST)	Postural stability (sway and limit of stability)	Shapiro-Wilk testing	The Biodex SD has strong test-retest reliability. Weak construct validity between TUG, FSST, and Biodex SD measures indicating more than one measure is needed to assess different aspects of a patient's balance deficits.
Estimating Berg Balance Scale and Mini Balance Evaluation System Test Scores by Using Wearable Shoe Sensors (58).	Berg Balance Scale Mini Balance Evaluation System Test Wearable sensor system embedded in the shoe and a hip accelerometer	Risk of fall	Correlation Bland-Altman plots Means and standard deviation	Wearable shoe sensors, used with support vector machine algorithm, can estimate the Berg Balance Scale and Mini Balance Evaluation System Test scores. The sensor measurements demonstrate high agreement with falls history.

A study mentioned by Massimo W. Rivolta *et al*. (56) combines the Tinetti clinical scale with a wearable accelerometer. The Tinetti score serves as a benchmark for effectively classifying individuals into high or low risk of falling based on variables derived from accelerometric data. The study highlights the significant correlation coefficient (0.71) between the Tinetti score and chosen features, demonstrating the strong potential of accelerometry-based movement analysis for assessing fall risk. Diverse techniques such as feature extraction, regression, classification, and correlation provide a comprehensive understanding of accelerometer data's predictive value.

In another study by Dawson *et al*. (57) focusing on the validity, reliability, and correlation of various balance assessment instruments, postural stability is the outcome measure. The study incorporates the Biodex Balance System SD, Timed Up and Go (TUG), and Four-Square Step Test (FSST). The study reveals strong correlations between the Biodex Balance System and TUG and FSST, indicating the instruments' reliability in assessing postural stability.

Additionally, a study by W. Tang *et al*. assesses balance assessment using a wearable sensor system's representation of scores from the Mini Balance Evaluation System Test and the Berg Balance Scale (58, 59). Using Bland-Altman plots, correlation analyses, and mean and standard deviation comparisons, the study suggests the intriguing potential of technology-based evaluations to produce reliable estimates comparable to those from conventional clinical balancing exams. The comprehensive methodology employed in this study underscores the promising role of wearable sensors in providing accurate assessments of balance.

These studies showed the promising alternatives that can be offered by using sensor-based measurements to complement traditional approaches yet, there is no one-size-fits-all system that can replace all conventional methods. Hence, clinicians can use the sensor-based systems for continuous measurements, objective scores and performance tracking but will still need certain conventional tests to identify other aspects of balance deficits that cannot be covered by a particular device. More studies comparing the sensor-based metrics and conventional balance assessments are still needed to provide a more comprehensive understanding of the capabilities and limitations of these systems.

5. CONCLUSION

Traditional balance tests may not always capture the nuanced issues of individual subjects and are often insufficiently sensitive. The demand for more sophisticated and rigorous testing methods by healthcare professionals is growing, particularly as previous methods may not comprehensively cover individuals at high risk of falls or those with severe neurological problems. Recent advancements in inertial sensor technology hold promise for improving the accuracy of dynamic balance assessments during clinical evaluations. Further research is necessary to explore sensor-based balance assessment as a potential replacement for traditional methods. It is suggested that sensor technologies can objectively measure both static and dynamic balance activities, providing insights into the efficacy and integration of motor control subsystems throughout the recovery process. The future of balance evaluation appears poised for a shift towards objective, technologically-enhanced methods. Such evaluations are likely to become the standard practice for managing patients with concussions, rehabilitating stroke survivors, and caring for the elderly. A comprehensive, adaptable, and sophisticated assessment, tailored to the individual's recovery phase and capable of challenging them sufficiently to gauge progress accurately, is recommended.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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