

Quantification of the Four-Stage Balance Test Using Plantar Pressure Map and Acoustic Wearables

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DISCLOSURE: Authors Schwab, Yazdkhasti, and Ghaednia hold the patent rights to the optical pressure mapping device and acoustic cuff that was used in this study.

INTRODUCTION: Quantifying balance is crucial for enhancing clinical diagnostics, optimizing rehabilitation, and improving quality of life. Poor balance can lead to falls, which may cause injury, disability, loss of independence, and healthcare costs which exceed \$50 billion annually in the United States [1]. The Four-Stage Balance Test (4SBT), recommended by the CDC, is a widely used method for assessing balance through postural control. Participants maintain progressively challenging standing positions (feet side-by-side, semi-tandem, tandem, and one-legged stance) for up to 10 seconds each. The CDC-4SBT provides fast assessment but is limited in scope. Test interpretation is subjective and measuring solely the duration a position is held overlooks valuable data on movement, posture, and control. Consequently, individuals with seemingly healthy balance may quickly pass all stages, limiting the detection of subtle balance difficulties. To address these limitations, we investigated two complementary devices: a plantar pressure mapping (PPM) platform and a wearable acoustic muscle monitoring cuff (AMMC), both developed by our group. The PPM device employs frustrated total internal reflection to capture dynamic, high spatial resolution maps of plantar pressure for precise center of gravity (CoG) calculations. The AMMC records variations in acoustic properties to capture muscle activation patterns. Together, these devices provide an objective assessment of balance that can be incorporated into clinical workflows. This study investigates the two devices and cross-validates their outputs against a series of clinical assessments and each other. Further, we generate a benchmark dataset to facilitate age-matched comparisons in future studies of balance impairments across orthopedic, neurological, and other clinically relevant conditions.

METHODS: We are enrolling a total of 200 healthy individuals with no history of spine or neurological disorders affecting lower limb function across three age groups (18-40, 41-65, and over 65 years, both male and female). Eligibility screening is conducted via email or phone, and informed consent is obtained during in-person study visits. This study was approved by the Institutional Review Board. Anthropometric measurements are obtained for each participant including weight, height, shoulder and hip widths, upper and lower body height, neck height, forehead perimeter and arm lengths. Participants also complete validated patient-reported outcome measures. These include the Patient Reported Outcomes Measurement Information System (PROMIS) scales for Anxiety, Pain Interference, and Physical Function, as well as the Quality of Life in Neurological Disorders (Neuro-QoL) assessments for Lower Extremity Function, Cognitive Function, and ability to Participate in Social Roles and Activities. Additional questionnaires include the CDC Stay Independent Questionnaire, the Modified Japanese Orthopedic Association (mJOA) Scale, and a custom survey assessing device comfort. Participants perform the 4SBT on a PPM device while wearing an AMMC on the right calf. The data acquired from these devices are conditioned, filtered, processed, and summarized. These processed datasets, together with anthropometric measurements and questionnaire responses, are compiled to form a comprehensive database.

RESULTS: We hypothesize that fluctuations in muscle activation measured by the AMMC are statistically correlated with both COG displacement captured by the PPM and clinical interpretations of the CDC-4SBT. Preliminary analyses suggest a relationship between muscle activation variability and CoG displacement, with data collection and processing ongoing to validate these findings across the full cohort (Fig. 1A-1B). Figure 1A presents the absolute mean error of CoG as a representation of sway in the coronal and sagittal planes for subjects (ages 25-80; even split male-female) across the CDC-4SBT tests. Notably, during poses that induce purposeful postural asymmetry, coronal sway exceeds sagittal sway, extending prior findings [2] that reported consistently larger sagittal-to-coronal sway ratios during normal standing where the coronal plane is most symmetrical, as is additionally reflected in our test 1 results. Figure 1B depicts fluctuations in muscle activity under the same conditions. As task difficulty increases, both CoG displacement and muscle activation variability demonstrate corresponding increases.

DISCUSSION: This study highlights the potential of biomedical devices and wearables for objective, high-resolution balance assessment. PPM and acoustic wearables provide complementary information, capturing CoG dynamics and muscle activation patterns, respectively. Preliminary data suggest that both measures increase with task difficulty, indicating sensitivity to changes in postural control not captured by traditional duration-based assessments. Further statistical analyses will in the future explore relationships between device metrics, CDC-4SBT performance, and demographic factors such as age and sex, providing insights into how balance varies across populations. These findings demonstrate proof of feasibility for high-precision quantification of balance and support the development of diagnostic, prognostic, and progress-monitoring applications in both clinical and research contexts.

CLINICAL RELEVANCE: Objective measurements from PPM and acoustic wearables can enhance early detection of balance impairments, support age- and sex-specific benchmarking, and inform individualized rehabilitation strategies. Whereas traditional duration-based assessments such as the CDC-4SBT are limited to subjective results, these devices hold the potential for analysis of a wealth of additional metrics, including plantar pressure peaks and regional foot segmentation, CoG trajectory dynamics beyond sway, and estimates of body composition. Integration of these tools into clinical practice may improve patient outcomes by providing precise and detailed quantitative insights into balance and musculoskeletal function. The benchmark dataset developed in this ongoing study offers a growing reference for future research across diverse populations and clinical conditions. Beyond fall prevention, precise balance assessment may also support early detection of musculoskeletal and neurological disorders, monitor medication effects, and optimize athletic performance.

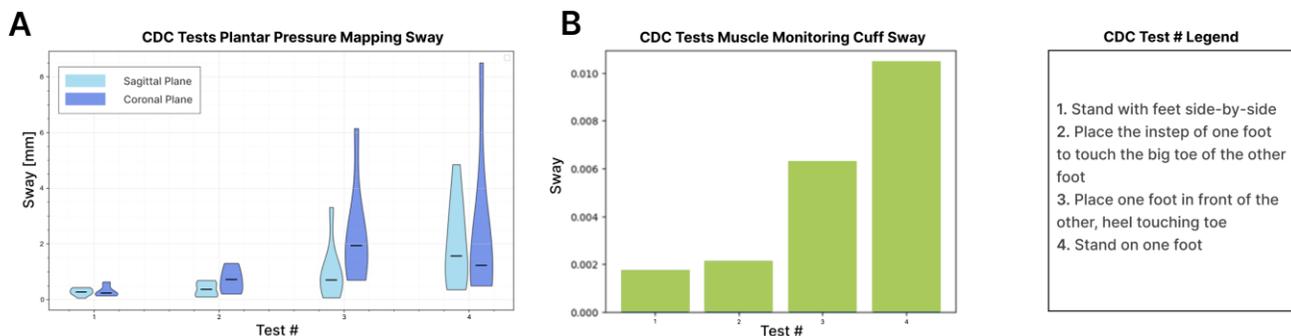


Figure 1. Sway measurements for the CDC 4-stage balance assessment. (A) Plantar pressure map device sway measurements. (B) Muscle monitoring cuff sway measurements.

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