Test-Retest Reliability of Remotely Administered Sway Balance and Cognitive Assessments

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ABSTRACT

Reliable remote monitoring of balance and cognitive function are critical when a qualified professional is unable to administer balance and cognitive functional assessments typically administered in-person. In this study recently completed in the Human Performance Laboratory at Wichita State Univesity, the test-retest reliability of remotely administered balance, reaction time, and cognitive function assessments developed by Sway Medical, Inc. (Sway) were investigated. Healthy adult participants (N=97) (average age = *35.2, SD= 13.8* years) across two sites (United States [N=65] and France [N=32]) completed the full battery of Sway balance and cognitive assessments twice during each of three sessions occuring one week apart, with test familiarization occuring during week one. A preliminary data analysis of remotely administered Sway balance and cognitive test batteries revealed strong to very strong reliability for Sway Balance (Spearman $\rho = 0.74$, $p < 0.001$), Simple Reaction Time (Spearman ρ =0 .70, $p < 0.001$), Impulse Control (Spearman $\rho = 0.73$, $p < 0.001$), Inspection Time (Spearman $\rho = 0.52$, $p < 0.001$), and Memory testing (Spearman $\rho = 0.52$, $p < 0.001$). Preliminary analysis of this study suggests that Sway balance and cognitive tests produce strongly reliable test-retest results when administered remotely by clinical professionals.

Keywords: cognitive testing, balance assessment, test-retest reliability, remote tests administration, digital health

INTRODUCTION

An important part of clinical assessment is the ability to reproduce consistent measures in time and space (Amick, Chaparro, Patterson, & Jorgenson, 2015; Burghart, Craig, Radel, Wu, & Huisinga, 2016; de Souza, Alexandre, & Guiraadello, 2017; Dunn, Bay, Cardenas, Anastasi, Williams, McLeod, & Williams, 2018; Seymour, Brashears, Roberts, Mock, Cleary, & Kasamatsu, 2015). An extensive body of independent third-party research performed at major research institutions across the United States and Canada have established the validity of the Sway Medical, Inc (Sway) balance and reaction time tests, as well as normative values in youth athlete populations. Moreover, the reliability of Sway balance and reaction time tests administered in-person have been well studied during intra- and inter-session testing in healthy and diseased populations. These Sway tests have shown a high-level of test-retest reliability (Burghart et al., 2016; Amick et al., 2015; Seymour et al., 2015).

Amick et al. (2015) evaluated reliability of the Sway balance test across three testing sessions with 24 healthy subjects (aged 25.96 ± 5.78 years) and found an excellent degree of inter-session reliability (ICC = 0.76). Intra-session reliability was excellent (ICC = 0.78 and 0.75 across sessions 1-2 and 2-3, respectively), indicating trial one provided familiarization. Similar ICC values for Sway balance test in a study of 18 youth athletes, 69 high school athletes, and 63 collegiate athletes by Dunn et al., (2018) revealed good to excellent test-retest reliability across three baseline tests after a familiarization (ICC = 0.66, 0.89, 0.83, respectively).

Similar inter-session reliability results were found with reaction time testing published by Burghart, et al. (2016). Four repeat measurements of Sway reaction time tests were performed with twenty-seven participants (aged 30.96 ± 12.07 years). ICC comparisons demonstrated significant reliability during repeated measurements for Sway tests (ICC = 0.71). A one-way ANOVA did not reveal statistically significant differences in Sway reaction times across sessions, indicating sufficient inter-session reliability.

More recently, Burghart and colleagues (2017) found similar ICC values for sway area, root mean square (RMS) distance, and mean velocity for both Sway and Center of Pressure (COP) measures taken from a force platform. Burghart concluded that, "SWAY is comparable in reliability to the gold standard force platform COP".

Additionally, a study of 31 healthy individuals (aged 20.4 ± 1.2 years) comparing reliability of balance scores collected using multiple validated devices for measuring balance (MobileMat, BioSway, mBESS, and Sway) was conducted by Seymour et al., (2015). Sway's balance test provided the most reliable internal consistency of all devices tested (Cronbach's $\alpha = 0.95$, all others were between 0.85 and 0.90).

Sway Balance and Cognitive Assessment Technology

Sway's patented balance assessment is a substantial improvement over current clinical assessments that require large stationary in-clinic equipment to measure an individual's postural stability. Sway's balance assessment requires no more than the mobile device that a user already owns. Consequently, the Sway balance test is an accessible and objective way of assessing balance for at-home and in-clinic users.

Similarly, Sway's proprietary motion-based assessment provides a much-needed alternative to cognitive testing devices requiring touch screen measurements. Using the built-in accelerometer of a mobile device, Sway allows for the collection of more accurate and consistent measures compared to touch-screen cognitive tests. Using the built-in motion sensors of the device, at a frequency of 500 to 1000 hertz (one to two milliseconds), Sway can measure within millisecond precision. Sway's patented method identifies the initial movement in response to a stimulus by detecting motion exceeding a threshold and identifies the first intentional motion in a given vector.

Collectively, the Sway application technology is an innovative solution to obtain objective, valid, reliable, and accurate balance and cognitive assessment data. The purpose of the current study was to study the test-retest reliability of remotely administered Sway mobile application tests.

MATERIALS AND METHODS

Design and Setting

Study participants from two geographic locations (United States and France) completed two virtually administered Sway cognitive and balance assessment trials once per week for three consecutive weeks, with a familiarization trial occurring during the first week. The research took place on a secured, password required Zoom video conferencing session through a link invite provided by the research administrators. The Wichita State University IRB approved informed consent form followed by study test instructions were communicated through Zoom by the research administrators. Participants were not charged a fee for using Zoom or the Sway Medical application. The testing protocol required approximately 20 minutes per session.

Participants

The study consisted of a combined 97 subjects (61% female) with an average age of 34.2 years old across both locations (United States [N=65] and France [N=32]) (Table 1). Participants were excluded if they had any of the following medical conditions (current or history of) known to impair balance and/or movement.:

- Musculoskeletal injury affecting functional movement and balance
- Neurological dysfunction
- Uncorrected vision
- Vestibular disorder or condition

Subjects without the necessary technology to maintain a Zoom connection throughout the assessment, and a smart-device capable of downloading and operating the SWAY application were also excluded from the study.

Table 1: Participant Demographics

	Female	Male	Total
Number (%)	59 (61%)	38 (39%)	97 (100%)
Age	35.2 ± 14.1	32.9 ± 14.5	34.2 ± 13.8
Height (cm)	163.6 ± 4.9	177.1 ± 6.8	169.5 ± 8.9
Weight (kg)	61.49 ± 8.9	82.6 ± 19.9	70.7 ± 17.8
BMI	24.0 ± 4.4	26.4 ± 5.5	25.0 ± 5.0

One male volunteer who met the neurological dysfunction medical criterion was excluded from the study. Two participants did not complete the study due to an unforeseen medical issue and due to time commitment constraints, respectively. Twenty subjects had missing data for at least one test session as a result of not pressing the application "done" button following completion of the test battery or internet disruption.

Measures and Procedures

Test Sessions

Each week, for three consecutive weeks (sessions), study participants completed two Sway balance and cognitive test battery trials – all trial tests are described below. Subjects rested for two (2) minutes between trials. A minimum of 7-days was required between the three sessions.

Balance Protocol

The user presses the mobile device against their chest and total postural stability, as well as raw acceleration waveforms, was measured during a modified Balance Error Scoring System (mBESS) protocol. The mBESS protocol requires a subject to stand and maintain balance while eyes are closed and feet together, during tandem stances (left foot front, right foot front), and single leg balance stances (left leg, right leg). The Sway balance score is a composite score that averages stability across all stances.

Instructions:

- Ex. "Stand with your feet together and eyes closed."

Motion Reaction Time Assessment

The Sway motion reaction time assessment ("Reaction Time") is a measure of basic sensory processing and neuromotor response speed. The test measures an individual's ability to detect a change in the color of the screen and quickly initiate a movement of the device. Simple reaction time (SRT) is the amount of time it takes to complete this task. Participants were standing in an upright position, while holding the mobile device with both hands. Participants were instructed to react to changes in the screen color by quickly shaking the device. Participants then performed SRT trials using the Sway Reaction Time test. Latent response times, which was the difference in time between the color change and the onset of user-initiated tilt of the mobile device, were recorded in milliseconds (ms). Participants completed two (2) trials of Sway Reaction Time testing, containing five (5) SRT tests each. Reaction time scores are determined from five (5) trials, measured in ms. The fastest and slowest trials were dropped and the average of the three (3) remaining trials were used in testing.

Instructions:

- "When the screen turns orange, move the device as fast as you can in any direction."

Impulse Control Assessment

The Sway Impulse Control test quantifies an individual's inhibitory processing time by presenting the user with either a go stimulus requiring a motion response, or a no-go stimulus requiring no response. The participant was asked to move the smart device as rapidly as possible in any direction when a target was presented on the screen.

Instructions:

- "When you see the green check mark, move the device quickly in any direction."
- "When you see the red x, keep the device still."

Inspection Time Assessment

The Sway Inspection Time assessment is a measure of rapid visual processing speed. Two T-shaped lines are presented, one twice the length of the other, for a short duration of time before they are masked. The participant was asked to touch the side of the screen with the longest line. The duration of time before the lines are masked was reduced as the user correctly identified which line is longer.

Instructions:

- "Two lines will be displayed before being masked. Tap the device on the side with the longer line."
- "Don't tap the device if you are unsure which line is longer. Incorrect responses will reduce your score."

Memory Assessment

The Sway Memory assessment measures visuospatial working memory. The test presented the user with a sequence of three consonants for 15 seconds. After the 15 seconds, the participant was asked to complete a working memory task by tracking a sequence of lighted squares. Once complete, the user was asked to recall the original three letter sequence.

Instructions:

- "Press begin test to reveal the three-letter sequence. You have 3 seconds to memorize the letters."
- "Watch the sequence until it is complete, then repeat the sequence."

Statistical Analyses

Data Preparation

Sway balance and cognitive test scores collected during the week 1 session were averaged for comparison to week 2 and 3 averaged Sway scores. As an example, trial 1 and 2 balance scores generated during the week 1 session were averaged and compared to an average balance score of week 2 session trial 1 and 2. In an effort to mimic real-world Sway scores and the probability of occasional outliers, outlying scores were not filtered from the data set. Generally, Sway considers test-retest scores varying more than ±30% in healthy individuals without acute injury are considered unreliable change outliers due to improper test administration or testing.

Test-Retest Correlation Analysis

Inter-session Sway assessment scores were analyzed using Spearman rank correlation analysis performed in Matlab (Mathworks, Inc.). The assumption of nonlinear relationship(s) between the data and the absence of human inter-rater (intra-) bias supported the use of Spearman rho (Liu, Tan, Chen, Lu, Feng, & Tu, 2016; Weir, 2005) instead of ICC, as shown to be used for analysis in other test-retest reliability studies (Amick et al., 2015; Burghart et al., 2016; Burghart et al., 2017; Dunn et al., 2018; Weir, 2005). Table 2 describes Spearman correlation coefficient interpretations. A statistically significance correlation rho was set at an alpha of p-value 0.05.

Table 2: Spearman Correlation Coefficient Interpretation

Spearman ρ	Correlation
≥ 0.70	Very strong
0.40-0.69	Strong
0.30-0.39	Moderate
0.20-0.29	Weak
0.01-0.19	Negligible

Adopted from *(Leclezio, Jansen, Whittemore, & de Vries, 2015).*

RESULTS

Primary Analyses

Three weekly test sessions (a familiarization test during week one, and two tests each week) were conducted and inter-session correlations between sessions 1 & 2, sessions 1 & 3, and sessions 2 & 3 were calculated to determine test-retest reliability. A preliminary data analysis of remotely administered Sway balance and cognitive test batteries show strong to very strong reliability for Sway balance (ρ=0.74, p<0.001), simple reaction time (ρ=0.70, p<0.001), impulse control (ρ=0.73, p<0.001), inspection time (ρ=0.52, p<0.001), and memory testing (ρ=0.52, p<0.001), as shown in Table 3, below.

The most consistent week to week reliability was seen in Sway Balance scores – session 1 & 2, Spearman rho = 0.71; session 1 & 3, Spearman rho = 0.77; and session 2 & 3, Spearman rho = 0.74. All Sway Balance test-retest correlations were statistically significant (p-value < 0.001) at alpha 0.05. Similar statistically significant correlation

Table 3: Reliability of the Sway Test Battery

	Balance	Reaction Time	Impulse Control	Inspection Time	Memory
	ρ *LB-UB*	*ρ* *LB-UB*	*ρ* *LB-UB*	*ρ* *LB-UB*	*ρ* *LB-UB*
Sessions 1_2 (n=84)	0.71*** (0.55-0.82)	0.67*** (0.51-0.79)	0.78*** (0.66-0.87)	0.52*** (0.31-0.68)	0.52*** (0.31-0.68)
Sessions 1_3 (n=83)	0.77*** (0.65-0.86)	0.72*** (0.56-0.82)	0.63*** (0.44-0.76)	0.41*** (0.18-0.60)	0.46*** (0.23-0.64)
Sessions 2_3 (n=77)	0.74*** (0.59-0.84)	0.72*** (0.57-0.83)	0.77*** (0.63-0.86)	0.63*** (0.44-0.77)	0.57*** (0.36-0.73)
Avg. *ρ*	0.74	0.70	0.73	0.52	0.52

*ρ, Pearson's rho; LB-UB, lower- and upper bounds; ***, p < 0.001; Avg. ρ, average Pearson's rho across all session*

results were found for test-retest reliability for Sway's Reaction Time and Impulse Control tests (both with p-value < 0.001).

While Sway Inspection Time and Memory test-retest Spearman correlations were lower than other Sway tests the correlations were still considered strong (Leclezio et al., 2015).

SUMMARY

Preliminary analysis of this test-retest reliablity study suggests that Sway balance and cognitive tests produce strongly reliable test-retest results when administered remotely by clinical professionals.

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