A validation of mobile sensing actigraphy devices for generating a biomechanical model of posture

Detheridge, Craig Neal
Thesis

A VALIDATION OF MOBILE SENSING ACTIGRAPHY DEVICES FOR
GENERATING A BIOMECHANICAL MODEL OF POSTURE

by

CRAIG N. DETHERIDGE

B.A., University of Maine at Farmington, 2014

Submitted in partial fulfillment of the
requirements for the degree of

Master of Science

2017
DEDICATION

I would like to dedicate this work to my parents, Kathy and Ray Detheridge, and my Godfather, Frederick Detheridge (Uncle Neal). Without the lifelong guidance and support that you have provided me, I would still be a child playing in the sand.

I would like to thank Dr. Kip Thomas for taking me under your wing, teaching me the business of science, and instilling the virtues of integrity and honor in my daily life.
ACKNOWLEDGMENTS

I would like to acknowledge the steadfast dedication that the research team portrayed during this study. The early mornings, long hours, cramped rooms, and monotony have evolved into something precious – simply because you made it so. Dr. Joanna Buczek, Chris Brooks, Alexandra Nutt, and John Caccaviello: Thank you.
A VALIDATION OF MOBILE SENSING ACTIGRAPHY DEVICES FOR
GENERATING A BIOMECHANICAL MODEL OF POSTURE

CRAIG N. DETHERIDGE

ABSTRACT

Mobile sensing actigraphy was tested and validated as a modality for computing
dynamic posturography. Twelve healthy volunteer subjects (6 male) were administered
risperidone and assessed for postural stability using a NeuroCom® Balance Master
system and BioSensics® mobile sensors at baseline, 2 hours, 6 hours, and 24 hours post-
dose. A strong positive correlation was shown between BioSensics and Balance Master
systems in a modified Sensory Organization Task, with Pearson’s $r = 0.76$, $p < 0.001$ on
composite equilibrium scores. Strong to moderate correlations during the same task
showed $r = 0.48$, $p < 0.001$ to $r = 0.74$, $p < 0.001$. Mobile sensing actigraphy may be a
viable alternative to force plate posturography in assessing drug-induced postural
instability.
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<td>ADT</td>
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<td></td>
</tr>
<tr>
<td>AP</td>
<td>Antero-Posterior</td>
<td></td>
</tr>
<tr>
<td>BU</td>
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<td>Center of Gravity</td>
<td></td>
</tr>
<tr>
<td>ECG</td>
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<td></td>
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<tr>
<td>MCT</td>
<td>Motor Control Test</td>
<td></td>
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<td>SOT</td>
<td>Sensory Organization Test</td>
<td></td>
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<td>SV</td>
<td>Sway Velocity</td>
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INTRODUCTION

Posturography refers to the assessment of postural control in upright stance in either static or dynamic conditions. Posturography, as assessed by the Balance Master and BioSensics systems, was compared for sensitivity and consistency. Previous studies have used the Balance Master system for assessment of gait and risk of fall in the elderly, persons with dizziness, stroke, spinal cord injury, and brain injury (Ben Achour Lebib, Missaoui, Miri, Ben Salah, & Dziri, 2006; Chien, Hu, Tang, Sheu, & Hsieh, 2007; Fraix, Gordon, Graham, Hurwitz, & Seffinger, 2013; Lemay & Nadeau, 2013; Liston & Brouwer, 1996; Newstead, Hinman, & Tomberlin, 2005). The BioSensics sensors were tested for comparability to the force plate system, as they are relatively inexpensive, more mobile, and potentially more robust due to using the two-link model of posturography rather than the inverted pendulum model.

Risperidone (RISPERDAL®) is indicated for the treatment of schizophrenia, and acute manic or mixed episodes associated with Bipolar I Disorder in the United States. It has been proposed that risperidone's therapeutic activity in schizophrenia is mediated through a combination of potent D₂ and serotonin Type 2A (5HT₂A) receptor antagonism (Foster & Goa, 1998). The potent D₂ antagonist is considered to improve the positive symptoms of schizophrenia, it causes less depression of motor activity and induction of catalepsy in animal models than classical antipsychotics, and a potent 5HT₂A antagonism has been shown to reverse deficits in several in vivo animal models predictive of novel antipsychotic activity (Megens, Awouters, & Niemegeers, 1988). Balanced central
serotonin and dopamine antagonism may reduce extrapyramidal side-effect liability.

Antagonism at receptors other than D₂ and 5HT₂ may explain some of the other effects of risperidone.

Further, risperidone has been chosen in this study since it represents a compound with a well-characterized dose to D₂ receptor occupancy-to-EPS relationship. It is expected that risperidone 2 mg will lead to D₂ occupancy of between 65-75% (Yamada, et al., 2002). These doses are considered appropriate since EPS liability relative to D₂ receptor occupancy is generally associated with D₂ occupancy >80%, and the objective is to validate mobile sensing actigraphy as a surrogate for force plate Computed Dynamic Posturography.

It is hypothesized that posturography will be a sensitive and objective means of detecting subtle changes in motor behavior modulated by striatal dopamine receptor 2 subtype (D₂) receptor occupancy associated with risperidone. The purpose of this study is to evaluate within- and between-subject variability and mean change on multiple modalities to assess mobile sensing. Posturography will be calculated via force plate (Balance Master™, NeuroCom, Pleasanton CA) and mobile sensing actigraphy (BalanSens™, BioSensics LLC, Cambridge MA).
METHODS

The study population consisted of a single cohort consisting of twelve (12) healthy individuals (6 males) ranging from 18-34 years of age with 2 dropouts (Table 1). Individuals who responded to recruitment materials underwent a screening phone interview consisting of a brief description of the study and asked questions to determine their eligibility. Potential subjects gave their formal verbal consent prior to the phone screening, and had an opportunity to ask questions about the study. Those who met the inclusion criteria and none of the exclusion criteria were invited to participate in the study. Eligible participants where scheduled for an in-person appointment to sign the consent form and complete the study. All study procedures were approved by the Institutional Review Board at The Boston University School of Medicine, and pharmaceuticals were obtained from the Investigational Research Pharmacy at Boston Medical Center.

All experiments took place in a dedicated lab space located at 650 Albany Street, Boston MA. The posturography tasks were administered by a trained administrator. Upon arriving at the Laboratory for Human Neurobiology, subjects reviewed and signed the Informed Consent Document, underwent brief intake procedures including electrocardiogram (ECG) evaluation and pregnancy tests (female subjects only). Subjects were excluded if their ECG showed a qT interval of >450ms. All subjects completed four testing sessions at Hour 0 (pre-dose

<table>
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<th>Variable</th>
<th>Value</th>
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<tr>
<td>Age</td>
<td>26 (+/- 4)</td>
</tr>
<tr>
<td>Height</td>
<td>(68 +/- 4.6)</td>
</tr>
<tr>
<td>Weight</td>
<td>167.6 (+/- 33.7)</td>
</tr>
<tr>
<td>BMI</td>
<td>25.2 (+/- 2.4)</td>
</tr>
</tbody>
</table>

Table 1 Mean (+/- Standard Deviation) Age, height, weight, and BMI
baseline), Hour 2, Hour 6, and Hour 24. Each testing session consisted of the following activities: blood pressure, pulse, device assignment, modified Sensory Organization Test (mSOT). Subjects remained at the laboratory for 7 hours after the administration of dose after which time subjects were released for the night to an accompanying escort.

Subjects were provided a $10 stipend and allowed time to eat lunch in between scheduled tasks. While not performing a task, subjects stayed in a private room and were asked to wait until the administrator notified them it was time to begin the next set of tasks.

Participants were financially compensated for their time and participation in the study at the completion of task activities.

**Device Placement**

During the mSOT task, the BioSensics sensors were placed on the lower back, and right shank (Figure 1).

This placement allows for a 2-link biomechanical model to be reconstructed, offering insight into postural sway and center-of-mass location (Najafi, Lee-Eng, Wrobel, & Goebel, 2015).

The sensors each weigh 25g, have a sampling frequency of 100 Hz, and use an accelerometer with a sensitivity of ±2g, and a gyroscope with a sensitivity of ±2000 deg/s.

![Placement of the BioSensics sensors during mSOT. Courtesy of BioSensics®](image-url)
Force Plate Equipment

A NeuroCom® SMART Balance Master system, version 9.2, was used (Figure 2). The system incorporates two foot plates, measuring 9 X 18 inches. Each foot plate rests on two force transducers to measure the vertical and horizontal force exerted by the left and right feet. The Center of Force of each foot plate is used to infer a vertical projection of the subject’s Center of Gravity (COG). The COG is assumed to be at 55% of the total height of the subject, and 14% of foot length in front of the medial maleolus bone in the ankle joint (Parker & West, 1973).

Modified Sensory Organization Task Protocol

The mSOT assesses a subject’s ability to maintain upright posture, and calculates the amount of antero-posterior sway that is exhibited. During the assessment, the subject is secured in a safety harness and faces the surround chamber of the Balance Master platform. The subject is instructed to remain as still and upright as possible, with their arms at their sides. Dependent on the condition, the platform may be fixed or dynamic and the surround may be fixed or dynamic, and the subject may be instructed to close their eyes (Figure 3). The force plate and surround during the dynamic conditions
exhibits “sway-referencing”, or the act of moving to exactly follow the subject’s sway and eliminate sensory feedback of sway motion. Sway-referencing forces the subject to rely on other sensory modalities, such as vestibular, when the vision and/or proprioceptive senses are compromised.

During the modified Sensory Organization Task, only conditions 1, 2, 4, and 5 are performed. Three trials of each condition, for 20 s each, are completed. If the subject touches the sides of the machine, looses footing, or is supported by the harness in any way, the trial is considered a fall.

**Figure 3** Sensory Organization Task Conditions. The mSOT consists of conditions 1, 2, 4, & 5. Courtesy of NeuroCom®
Calculations

The same equations are used for the Balance Master system as are used for the BioSensics sensors.

**Sway Angle**  The antero-posterior (AP) sway is originally measured as the centimeters in which the COG travels forward and back. However, this sway must be normalized to allow for between-subject analysis due to the variability in the height of the COG due to subject height. To normalize sway, the AP Sway Angle is calculated using the following equation:

$$\theta = \arcsin\left(\frac{P_{COG}}{H_{COG}}\right) - 2.3^\circ$$

Where $\Theta$ is the AP Sway Angle, $H_{COG}$ is the Height of the COG, and $P_{COG}$ is the instantaneous position of the COG. The formula takes into account the 2.3° of forward lean that the human body naturally exhibits when standing erect. The small angle approximation by use of arcsine is accurate to within 0.5% in these use-cases, and thus appropriate for estimation.

**Equilibrium Score**  In order to quantify and differentiate “normal sway” from “pathological sway”, an equilibrium score is calculated. This score assesses how well the subject remains within the theoretical angular limits of stability of the human body, which is theorized to be 8 degrees forward and 4.5 degrees back. The following equation is used:

$$Equilibrium\ Score = 12.5^\circ - \frac{(\theta_{max} - \theta_{min})}{12.5^\circ} \times 100$$
The score has an inverse relationship with sway, meaning that a high score will depict little sway and a low score depicts much sway. A fall is considered a score of 0.

**AP Sway Velocity** The Sway Velocity (SV) is the distance traveled by the COG, in degrees, over the time of the trial. The following equation is used:

\[
Sway \, Velocity = \frac{(|\Delta \theta|)}{t}
\]

Where \( \theta \) is the AP Sway Angle, and \( t \) is the trial time in seconds.

**Equilibrium Composite Score** A composite score of each trial and each condition of the mSOT is comprised of a weighted average of each of the conditions, using the following equation:

\[
\text{mSOT Composite Score} = \frac{(\text{Avg}(\text{SOT} - 1) + \text{Avg}(\text{SOT} - 2) + \text{Trial}_1(\text{SOT} - 4) + \text{Trial}_2(\text{SOT} - 4) + \text{Trial}_3(\text{SOT} - 4) + \text{Trial}_1(\text{SOT} - 5) + \text{Trial}_2(\text{SOT} - 5) + \text{Trial}_3(\text{SOT} - 5))/(3\text{trials}(\text{SOT} - 4) + 3 \text{trials} (\text{SOT} - 5) + 2 \text{trials}(\text{SOT} - 1 \text{ and } \text{SOT} - 2))}{(3\text{trials}(\text{SOT} - 4) + 3 \text{trials} (\text{SOT} - 5) + 2 \text{trials}(\text{SOT} - 1 \text{ and } \text{SOT} - 2))}
\]

**RESULTS**

**Blood Pressure and Heart Rate** Subjects’ mean systolic and diastolic blood pressure were higher at baseline than at subsequent assessments. Subjects’ mean heart rate remained within 2.5 bpm throughout assessment periods. Mean values are demonstrated in Table 2.

**Table 2** Mean (+/- Standard Deviation) blood pressure and heart rate as assessed at sessions pre- and post-dose.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Baseline</th>
<th>Hour 2</th>
<th>Hour 6</th>
<th>Hour 24</th>
</tr>
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<tbody>
<tr>
<td>Systolic blood pressure (mmHg)</td>
<td>122.8 (+/- 18.6)</td>
<td>119.0 (+/- 18.4)</td>
<td>118.0 (+/- 17.0)</td>
<td>117.5 (+/- 14.0)</td>
</tr>
<tr>
<td>Diastolic blood pressure (mmHg)</td>
<td>77.5 (+/- 10.4)</td>
<td>71.5 (+/- 9.7)</td>
<td>69.8 (+/- 10.3)</td>
<td>71.3 (+/- 9.3)</td>
</tr>
<tr>
<td>Heart Rate (bpm)</td>
<td>76.6 (+/- 14.4)</td>
<td>74.2 (+/- 13.4)</td>
<td>77.2 (+/- 13.1)</td>
<td>73.5 (+/- 9.1)</td>
</tr>
</tbody>
</table>
mSOT Equilibrium COMPOSITE Scores

Balance Master demonstrated a general upward trend in composite equilibrium scores from Hour 0 to Hour 24, as shown in Figure 4. BioSensics demonstrated a reduction in performance at Hour 2 and Hour 6 with a general upward trend in equilibrium scores from Hour 0 to Hour 24. Pearson’s Product-Moment Correlation between Balance Master and BioSensics composite scores demonstrated a strong positive correlation of $r = 0.76$, $p < 0.001$.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Figure4}
\caption{mSOT Equilibrium Composite Scores for Balance Master (left) and BioSensics (right). Trial mean represented as a bold blue line. Mean equilibrium scores at each time point represented by black triangles. Gray shading indicates the 90\% confidence interval.}
\end{figure}
Sway Velocity

During each condition, sway velocity increased at peak dose and initial washout (i.e. Hour 2 and Hour 6), suggesting a pharmacodynamic disturbance on postural stability (Figure 5).

Correlations between Balance Master and BioSensics sway velocity scores were the following: Condition 1 $r = 0.57$, $p < 0.001$; Condition 2 $r = 0.48$, $p = 0.001$; Condition 4 $r = 0.63$, $p < 0.001$; Condition 5 $r = 0.74$, $p < 0.001$.

![Figure 5](image-url)  
*Figure 5* Sway velocity scores for both the Balance Master (BM; top row) and BioSensics (bottom row) systems during the mSOT tasks. Trial mean represented as a bold blue line. Mean equilibrium scores at each time point represented by black triangles. Gray shading indicates the 90% confidence interval.
DISCUSSION

There are fundamental differences in the measurements collected by the NeuroCom® Balance Master system and the BioSensics. Most importantly is the distinction between the biomechanical models used to compute posturography from a fixed number of points.

The Balance Master system assumes the “inverted pendulum” model, as shown in Figure 6. This model assumes that a human’s Center of Gravity may be calculated based on a measurement of the Center of Pressure of the feet, and that the COG may be extrapolated from the angle at which the shank extends from the ankle. One major flaw in this assumption is the failure to acknowledge the role of the hip and knee in vertical posture.

Conversely, the BioSensics sensors in this array utilized a two-link biomechanical model. This model factors both ankle and hip angles to determine the Center of Gravity. The two-link model has been found to be more effective in accurately determining the trajectory of a Center of Gravity (Najafi, Lee-Eng, Wrobel, & Goebel, 2015).
Although the correlation between the reference technology (force plate system) was not a perfect $r = 1$, the validity of the force plate may be brought into question. The assumption of validity is necessary, as force plate technology is currently the industry gold standard in posturography, however the lack of complete correlation should not insinuate insufficiency in mobile sensing technology.

The differences in measurement are more clearly demonstrated in the Sway Velocity measurement. In this study, only the antero-posterior dimension was used. A limitation of mobile sensing actigraphy is that the axes of measurement are dependent on the placement of the sensors on the body. If there is a rotation about the z-dimension, such as a shifting of the sensor around the shank or waist, the amount of AP sway will be inaccurately underestimated. This may account for the observed difference in AP Sway Velocity, although the correlations were still moderate ($r = 0.46, p < 0.001$) at worst and strong ($r = 0.74, p < 0.001$) at best. In future studies, it may prove more robust to measure both medio-lateral and antero-posterior sway velocity and generate a 2-dimensional ellipsis of sway.

During the mSOT trials, the Balance Master system assigned a score of 0 to a fall. This assignment was necessary as the force plate is unable to properly track COG trajectory if a foot is displaced or lifted. The BioSensics sensors, however, were able to continue measuring COG displacement when a subject lifted a foot or fell.

The portability of the mobile sensors is a major logistical benefit to the technology over force plates. In a purely practical sense, a force plate system may prove unfeasible to fund or relocate in clinical use. The mobile sensors have the
benefit of fitting in a suitcase. Additionally, mobile sensors have the possibility of being used in a use-case that would not allow for a force plate; such as a subject in motion or performing an activity that would require the feet to leave the ground.

One limitation of this study was the limited number of participants. The confidence intervals exhibited statistical significance, although there was not homogeneity among the observed effects of risperidone on all participants. For example, a majority of subjects demonstrated diminished postural stability at peak dose and initial washout (2 and 6 hours post-dose). However, some subjects demonstrated increased performance on the mSOT during these periods. A possible explanation for this phenomenon would be subject variables that were not collected at the time of recruitment, such as participation in athletics or the use of public transportation as a primary means of commuting. If a participant was an athlete, they would have had a greater exposure to activities that strengthen postural alignment and stability. An athlete would likely have greater control over Center of Gravity trajectory in comparison to a non-athlete. If a participant utilized public transportation, they would have more practice with maintaining an upright posture during times of unexpected perturbation than a commuter who drives. A subway or bus rider must learn to use proprioceptive and visual feedback to overcome the vestibular sense, in order to commute without falling.

Another limitation of the study was the absence of “practice trials”. There is an insufficiency in the literature regarding this effect, as it has not been clearly tested or reported. The learning effect is a commonly observed phenomenon in
novel activities, which may have taken place during this study. Some participants steadily performed better during each assessment, while the expected pharmacodynamic effect would have been decreased performance while under-drug and a return to baseline after washout. An experiment to test the practice effect is necessary, and could be accomplished by running healthy volunteers under the same conditions over many days to examine the time-to-plateau.

**CONCLUSION**

Mobile sensing actigraphy has been demonstrated as a viable alternative to traditional force plate posturography. The BioSensics® sensors, using a two-link biomechanical model, exhibited similar patterns of Equilibrium Score and Sway Velocity as compared to the NeuroCom® SMART Balance Master system. This study showed strong-to-moderate consistency between the systems, depending on the endpoint. Further investigation into practice effects, subject confounds in drug research, and the optimal number and placement of sensors is necessary before mobile sensing has enough validity and reliability to be used in the clinical environment. Replication of this study with a greater number of participants is recommended.
REFERENCES


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December 2014
- Northeast Undergraduate Research & Development Symposium, Best Oral Presentation
- UMF Research Symposium, Select Speaker Award for Research Study – “Inducing Relaxation via Virtual Reality”
- Relevant Coursework: Abnormal Psychology, Research Methods & Design, Organizational Psychology, Human Resources Management

Research Experience

- “A Multimodal Evaluation of Circadian Rhythm”
  Central Role: Data Acquisition & Management
  - Device Management - Responsible for actigraphy device configuration, troubleshooting, data upload, file management, and vendor communication.
  - Data analysis – Responsible for formatting data architecture and producing analyses of circadian patterns using “RADA” software (Rapid Actigraphy Data Analysis, Philips).
  - Data Management – Responsible for file architecture management, quality assurance of data integrity, and database management.

- “Evaluation of a Mobile Application and Two Actigraphy Devices in Subjects with Parkinson’s Disease and Healthy Volunteers”
  Central Role: Study Coordinator
  - Subject Management - Responsible for recruitment, screening, and scheduling of participants, in collaboration with the Michael J. Fox Foundation. Responsible for administration of clinical and psychometric assessments.
- Device Management – Responsible for device configuration, maintenance, and troubleshooting, along with data upload and storage.
- Staff Management – Responsible for staff training, scheduling, management, and coordination.

Awards
- Northeast Undergraduate Research & Development Symposium
  - Best Presentation; “Inducing Relaxation via Virtual Reality”
  - University of New England, April 2014
- University of Maine at Farmington Research Symposium
  - Select Speaker Award
  - UMF, May 2014
- Rotary Youth Leadership Award
  - Mount St. Mary College, July 2009