Translating the science of balance:
Rehabilitation based on quantification of sensory integration

Part 1
Laurie King, PT, PhD
Leslie Allison, PT, PhD
Geetanjali Gera, PT, PhD
Mike Studer, PT, MHS, NCS, CEEAA, CWT, CSST

Conflict of Interest
No authors have a conflict of interest

Objectives
• Following completion of this course, participants will be able to:
• I. Discuss the scientific rationale for and clinical benefits of measuring sensory integration in the clinic.
• II. Understand the quantification and interpretation of sensory deficits in postural control using inertial sensors or force plates to measure postural sway.
• III. Explain potential rehabilitation interventions that address specific sensory integration deficits.

Incidence of Balance Problems
• Approximately 1/3rd of individuals over the age of 65 fall annually
• Over 2/3rds of individuals over the age of 80 fall annually
• Falling is the leading cause of injury and death in elderly adults
  – Over 700,000 patients a year are hospitalized because of a fall injury
• 90% of hip fractures in the elderly population are attributed to falls
• Older adults with neurological gaits have a 49% increased risk for falls compared to subjects without neurological gaits

What is Balance?
If therapists think of balance as a static state, that is how they will assess balance in the clinic.

Balance is not static

Center of Mass (COM)
– Theoretical point about which an object pivots in equilibrium
– Weighted average of the mass of your body- projected down to surface

Center of Pressure (CoP)
– Theoretical position under the base of support through which all forces act on the body.
What is Balance?

- Control of the Center of body mass (CoM) relative to the base of support.
- Producing forces against the surface that complement and coordinate external forces due to gravity, interaction with environment (ie moving head) and internal forces (ie interaction torques) associated with movement.

The Balance Evaluation Systems Test (BESTest)

Differentiate Balance Deficits Fay Horak, Diane Wrisley, James Frank, Physical Therapy 89(5), 2009

www.BESTest.us

SOT in itself is not sufficient to detect balance deficits in PD

Gera et al. In Review

Sensory Integration and Balance

(Peterka and Loughlin 2004)

Visual system for balance

- Visual fields
- Depth perception
- Communicate with vestibular nuclei
- VOR to stabilize image on retina
  - Head turns right
  - Excitatory impulse from right semi circular canal to right vestibular nuclei
  - Excitatory fibers cross to the left lateral rectus (along with inhibitory to the right medial)
Vestibular system for balance

Vestibular nuclei communicate with:
- Cerebellum
- Cranial nerves for eye movement
- Vestibular spinal tract (postural control)

Central integration for balance

- 4 vestibular nuclei
- Enters into brain at medulla and splits ascending and descending
- Projections to:
  - Ventral horn of spinal cord via vestibulospinal tract
  - Cerebellum
  - Abducens, trochlear oculomotor nuclei

Conceptual model of human balance control

Modified from: Johansson, Magnusson et al. 1988

Proprioception for balance

Postural Sway

“Postural Sway” refers to small postural shifts from front to back and side to side, during quiet stance.
How do we measure sensory reweighting?

Sensory re-weighting

<table>
<thead>
<tr>
<th>Sensory System</th>
<th>Contribution to Balance Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vestibular</td>
<td>17% 32% 23% BVL</td>
</tr>
<tr>
<td>Visual</td>
<td>33% EC 77% EC</td>
</tr>
<tr>
<td>Proprioception</td>
<td>50% 68% Sway Ref 100%</td>
</tr>
</tbody>
</table>

Sensory weights derived from sway responses evoked by very low amplitude surface or visual motion stimuli.

EC = Eyes Closed
BVL = Bilateral Vestibular Loss
SR = Sway Referenced

Peterka 2002

Bilateral vestibular loss

Patients with unilateral vestibular loss who have the largest vestibular weight, show the best functional recovery

Rehabilitation should train vestibular subjects to use what remaining vestibular function they have and not depend only on somatosensory and vision.

Peterka, Statler et al. 2011

mTBI; why consider sensory integration

Head injury can lead to imbalance, dizziness, vertigo (24-83%)

• Abnormalities of peripheral vestibular function (Akin and Mumane 2011).
  • the semicircular canals can be affected in about two-thirds of patients with mTBI. (Davies and Luzon 1995, Toglia, Rosenberg et al. 1970)
  • the otolith organs are susceptible to damage from mTBI. (Ernst, Basta et al. 2005)
  • ocular motor deficits (Capo-Aponte, Unsworth et al. 2012, Ventura, Balser et al. 2014) (saccade latency is extended in patients with mTBI (Drew, Langan et al. 2007). Pursuit is also affected in patients with mTBI.
  • Sensory integration may also be impaired (acute and subacute n=500SM; impaired visual and vestibular scores. (Haran et al. 2015)
Questions

- How can we measure central sensory integration and can we trust and interpret findings
- Can we use rehabilitation to change maladaptive strategies for central sensory integration and weighting.

Novel approaches to quantify & interpret sensory integration for balance

Part II Measurement of Multi-Sensory Integration

Leslie Allison, PT, PhD
CSM 2016
Anaheim, CA

OBJECTIVES:

- Differentiate between MSI assessment & balance performance
- Analyze what is being assessed during MSI testing
- Recognize the benefits and limitations of how balance performance is tested
- Correctly interpret MSI contributions to balance performance

References

What do ‘clinical’ tests of sensory integration actually measure?

**inputs .....**

```
Somatosensation
  Proprioception
  Vibration
  Kinesthesia
  Pressure
  Touch
  Etc.

Vision

Vestibular
  Gravity
  Verticity
  Acceleration
  Deceleration
```

**outputs .....**

```
Postural Alignment
  "Posture"
  Verticity

Postural Sway
  Static (Hold Still)
  Dynamic (L.O.S.)

Postural Responses
  Reflexes
  Automatic
  Anticipatory
```

Clinical tests of multi-sensory integration

- Systematically manipulate the environment
- Control the availability & accuracy of sensory inputs
- Measure postural control in various environmental conditions

Clinical tests of multi-sensory integration

- We interpret environment-related changes in postural control as evidence of sensory integration
- We infer:
  - sensory integration is intact or deficient
  - Use of specific sensory inputs is normal or abnormal
Why measure sensory “input” components of the postural control system?

Why measure motor “output” components of the postural control system?

“Romberg’s sign” test

Romberg’s test [pub. 1840-1846]: positive due to sensory ataxia (Khasnis & Gokula, 2003)

Moritz Heinrich Romberg

Tabes dorsalis (syphilitic myelopathy)

‘Sharpened Romberg’ Test (Fregly, 1974)

Limitation of time as a postural control measure

Test sensitivity improved by measuring postural sway

Swaymeter (Ljord SR et al, 1992)

Inclinometric single-link pendulum device (Vilasalo MK et al, 2002)
Sensory organization test
(nashner et al, 1982)

Sot test characteristics
(www.rehabmeasures.org)
- Time to administer: 15 min
- Training: suggested, not required
- Equipment: Equitest®, SMART Equitest®, or SMART Balance Master®
- Tested on multiple populations
- Test-Re-test reliability
  - Composite score: .67
  - Various single conditions: .35 - .79
- Discrimination of vestibular disorders
  - Sensitivity = 85%
  - Specificity = 77%

Clinical test of sensory interaction on balance
(Shumway-Cook A & Horak FB, 1986)

CTSIB Test characteristics
(www.RehabMeasures.org)
- Time to administer: 10-20 min
- Training: not required
- Equipment: stopwatch, foam, dome
- Tested on multiple populations
- Test-Re-test reliability
  - Composite score: .75-.91 depending on population
- Discrimination of vestibular disorders
  - Not reported

Comparison of sot & ctsib
(weber & cass, 1993; El kashlan et al, 1998)
- Both can detect ‘sensory balance abnormalities’
- SOT, but not CTSIB, can discriminate between somatosensory vs. vision vs. vestibular problems
- Foam = sway-referenced forceplate
- Dome ≠ sway-referenced visual surround

Modified, instrumented
Clinical test of sensory interaction on balance
Modified, instrumented CTSIB Test characteristics

- Time to administer: 10-15 min
- Training: suggested, not required
- Equipment: Balance Master®, PRO Balance Master®, foam
- Tested on multiple populations
- Test-Re-test reliability
  - Composite score: 91-97 healthy
- Discrimination of vestibular disorders
  - Not reported

Accelerometry sensors

Wearable sensors

What do clinicians need to consider before attributing balance problems to multisensory integration impairments?

Many postural control system components affect balance performance

Interpretation of results & inference of MSI deficits are straightforward when:

- Normal
- Abnormal result
Interpretation of results & inference of MSI deficits are complicated when:

- Abnormal result
- Unilateral/bilateral decrease in somatosensory, vision, vestibular
- Slow reaction time
- Hypometric scaling
- Influence of fear
- Unilateral/bilateral decrease in ROM, strength, endurance
- Central Motor Planning & Programming

Take Home Messages

- All critical postural control components – including but not limited to MSI - should be assessed
- Quantifiable measures of postural sway permit better detection
- Early/substrate MSI problems
- Change in MSI over time
- Wearable sensor accelerometry offers accurate & reliable measurement

Many postural control system components affect balance performance

Quantification of Sensory Integration Deficits

Geetanjali Gera, PhD, PT
Post-doctoral researcher
OREGON HEALTH AND SCIENCE UNIVERSITY

References


Bachelor in Physical Therapy from Post-graduate Institute of Medical Education and Research, Chandigarh

BS and PhD University of Delaware Human Motor Control (Coordination deficits in stroke and aged individuals)

Post-doctoral Researcher Balance Disorders Laboratory

Geetanjali Gera, PhD, PT
Limitation of time as a postural control measure

Stopwatch is sometimes not enough

Computerized Dynamic Posturography (CDP/SOT) (Nashner et al, 1982)

Interpretation of sensory conditions

Clinical test of sensory interaction on balance (CTSIB) (Shumway-Cook A & Horak FB, PTJ, 1986)

Modified Clinical test of sensory interaction on balance (mCTSIB)
Demonstration of Modified CTSIB

No dome condition as in CTSIB because impractical to use

Computerized Dynamic Posturography

- Computerized Dynamic Posturography (CDP):
  - Clinically useful due to ability to elicit specific inputs
  - Can be used as gold standard to identify sensory integration deficits
- However, forceplates and CDP:
  - Relatively immobile
  - Expensive
  - Limited variables/measures
- Finding other less expensive/more informative methods has been of interest

Inertial sensors validated against force plate

- Inertial sensors are valid, reliable and sensitive measure of postural sway
  - Mancini 2012

Comparison of Computerized Dynamic Posturography and Accelerometry

- Accelerometry correlated well with COP during SCT conditions. Whitney et al. 2011
- Thus, acceleration can be used as a substitute to COP
- Next Step: To use accelerometry (inertial sensors) in assessing sensory integration deficits with clinical tools (Modified Clinical Test of Sensory Integration of Balance (mCTSIB))

Sensory Organization Test versus Instrumented mCTSIB

- Computerized Dynamic Posturography: Peak to Peak Excursion of COP
- Inertial Sensors: Multiple measures for AP as well as ML sway (including absolute magnitude and variability measures)
Instrumented Modified (m)CTSIB validated against SOT

Validity of instrumented mCTSIB to Measure Postural Control in Persons with Subtle Impairments: A Pilot Study (Paper in Review)
D. Lynn Freeman, PT, PhD, Geetanjali Gera, PT, PhD, Mary T. Blackinton, PT, EdD, GCS, Fay B. Horak, PT, PhD, Laurie King, PT, PhD

Interpretation of sensory conditions

Sensory integration deficits in neurologic population

Multiple Sclerosis

Balance Deficits during Quiet Standing in MS

Standing Eyes Open versus Eyes Closed in People with MS

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Standing Eyes Open versus Eyes Closed in People with MS
Standing Eyes Open versus Eyes Closed in People with MS

EO Firm
EC Firm

HC
PwMS

Total Sway Area (mm²/s)

Fling et al. 2013

Parkinson’s Disease

• PD subjects might have subtle deficits in sensory integration, which might go undetected with stopwatch measures.
• Some deficits might be related to aging and not the disease per se.

Computerized Dynamic Posturography in PD

Large group of PD subjects (N=102), postural sway was normal in the group of never-treated, very early stage PD subjects but was abnormal in the group of PD subjects with a UPDRS III>20 and increased with disease severity, when tested off-state.

Sensory Impairments is not the only factor for postural instability in PD

12 patients with PSP, 12 idiopathic PD, and 12 healthy controls were tested. UPDRS~34. PSP subjects performed poorly compared to PD subjects and controls in conditions 4, 5, and 6 of the SOT, when tested off-state.
Traumatic Brain Injury

Mild Traumatic Brain Injury (TBI)

Summary

Sensory integration deficits can differ across patients even within the same diagnosis

- MS: Many but not all people with MS are visually dependent
- PD: Many PD people have normal sensory integration but not all
  Abnormal sensory integration could be related to co-morbidities (Aging, motor weakness etc.)
- PSP: Definitely have more problems with perception of proprioception (somatosensory dependence)
- TBI: Struggle with more complex sensory integration condition, could be attributed to vestibular deficits/ central integration deficits

Interpretation of results & Clinical Implications

- Important to assess each patient individually and customize therapy accordingly
- Quantification of sensory integration deficits can help in assessing and tailoring the treatment plan accordingly
- Determine where the problem lies:
  - Sensory input
  - Central integration
  - Other factors: Motor, cognitive or other co-morbidities
  - Something else?
- Two therapeutic approaches (targeting sensory reweighting)
  - Preserve: maximize use of remaining sensory input (Constrained sensory integration)
  - Compensate: teach to compensate if loss is irreconcilable (for example, patient with a bilateral vestibular loss might benefit from light touch)
• Working on normative data: to define norms:
  • Romberg Quotient
  • What does this all mean to clinicians
  • Sensitive measures
  • Central integration deficits
  • Vestibular problems
  • Somatosensory deficits

Despite impairments individual subjects with MS can learn to improve postural prediction

Some suggestions...

SOT (Neurocom)
We know that SOT is good in differentiating among visual, vestibular and somatosensory deficits but not CTSIB.

Maybe because not very sensitive?

Coming up with better ways to differentiate these and making sensory assessment portable

Vestibulary deficits are present in PD, TBI and MS, SOT?

PD?

CTSIB?

MS: better in sensory way

Working on getting the normative values: to define what is normal and what is abnormal.

With other measures: medio-lateral sway, frequency etc. one can gather more information on what is going on and tailor therapy accordingly.

In large scale thing of input and output, it is still not clear why this is happening; possible issues: sensory deficits, central integration problems.

If the peripheral measures are available, harness that to work on neuroplasticity principles to strengthen the central integration. For example, a person with MS: working with eyes close, so that can use whatever is left or can use additional pathways.

Vestibular deficits: central/peripheral vestibular problems or central integration deficits

1. Slide 3 should be Neurocom Equitest current approach: discuss what it means to have visual dependent, surface dependent and vestibular loss patterns and implications for rehab

2. Add slide 6 of results from Suan Whitney showing that assist on belt is as good as measures for sway in 6 sensory conditions

3. Mention: The CTSIB doesn’t include the visual surround as too impractical (although some few vestibular and head injury may be sensitive to sway ref visual surround)

4. Summarize what these patient examples showed. We are visually dependent too (so) PD can be normal although TBI more than any other neurological condition but PD are very surface dependent (they also fall backward spontaneously) and central sensory is bovinebellated (also TBI). Also exchange what was not done but necessary in this case and how we gathered information such as if one can stop wobbly may have no deficits as cannot treat these impairments.

6. Better to put references in slides and not at end

7. Add acknowledgments with lab photo at end
Multisensory Integration: Case Studies and Applications

Mike Studer, PT, MHS, NCS, CEEAA, CWT, CSST

Neuroplasticity Principles

1) Use it or Lose it: Failure to drive a specific brain function can lead to functional degradation
2) Use it & Improve it: Training that drives a specific brain function can lead to an enhancement of that function
3) Specificity: The nature of the training experience dictates the nature of the plasticity
4) Repetition Matters: Induction of plasticity requires repetition
5) Intensity Matters: Induction of plasticity requires sufficient training intensity

Kleim and Jones 2008

Neuroplasticity Principles

6) Time Matters: Different forms of plasticity occur at different times during training
7) Salience Matters: The training experience must be sufficiently salient to produce plasticity
8) Age Matters: Training-induced plasticity occurs more readily in younger brains
9) Transference: Plasticity in response to one training experience can enhance the acquisition of similar behaviors
10) Interference: Plasticity in response to one experience can interfere with the acquisition of others

Kleim and Jones 2008
Multisensory Integration:
BEYOND “Eyes closed and foam”
Applications in:

- Static balance*
- Dynamic balance*
- Extremity “remapping”: protective efforts
- Extremity “remapping”: functional contribution

* MSI

MSI: Static Balance

- Perception of vertical
- Reaction speed
- Reaction accuracy
- Capacity to ANTICIPATE and create a feedforward set
- Vision restricted (eyes closed, head motion, distraction)

- Principles of dosage
- Role of fear of falling, failing
- Role of personality

MSI: Dynamic Balance

- Perception of vertical
- Reaction speed
- Limb placement accuracy
- Monitoring motor control of the task and balance
- Capacity to ANTICIPATE and create a feedforward set
- Vision restricted (eyes closed, head motion, distraction)

- Principles of dosage
- Role of fear (falling and joint damage)
- Role of personality

MSI: Static Balance

MSI: Dynamic Balance

Agility Vision (closed or other) Distraction

(All of these, while in motion)
MSI - Extremity “remapping”: “Opportunistic Use Therapy” = OUT
Reweighting through survival/protective efforts

- Grasp/stabilization: reliability in closing the chain
- Indications/contraindications
- Role of fear (falling and joint damage)
- Role of personality

MSI - Extremity “remapping”: functional contribution
Reweighting through salience

- Meaningful tasks
- Fun tasks
- Sensory manipulation
- Intensity vs. error
- Role of personality

MSI - Extremity “remapping”: functional contribution
Reweighting through salience and sensory manipulation

Case Studies
- Neuropathy: Expectations for sensory input
- Stroke: Forced sensory experiences for recovery
- Multiple Sclerosis: Reweighting for efficiency**
- Parkinson’s Disease: Perception of vertical

Case Studies: Neuropathy
- 73 yom w idiopathic neuropathy
- Essentially insensate feet/distal
- Expectations for sensory information with head rotation
- Compare sway with head rotation vs. head stable
- Retrain balance strategies with experience/exposure
• 44 yom s/p L ICH aneurysm
• Severe R hemiplegia
• Making RUE sensation important to protect from a fall
• RUE in optimal position to help
• Brain chooses to use R UE and process sensory information

• Severe visual dependence
• Fear of falling with anxiety
• Progressive aberrant visual signal
• Static -> dynamic
• Increasing speeds in BWSTT
• Transition to level ground
• Cues to process somatosensation

• Sense of vertical
• Retropulsion or festination
Future of MSI

• Virtual reality and holograms?
• Graded motor imagery
• Visualization/mental practice
• Cost/benefit

References


Questions?


Contact information

• Laurie King: kingla@ohsu.edu

• Leslie Allison: Allisonk@wssu.edu

• Geetanjali Gera: geetanjaligera@gmail.com

• Mike Studer: mike@northwestrehab.com

References


