Whole-Body Vibration Exposure in Construction: Examining Acute Effects, Guidelines, and Risk Mitigation Strategies to Prevent MSD and Injuries

Marcus Yung, PhD, CPE
Bronson Du, MSc.
Today’s Webinar

1. Examine the acute effects of WBV,

2. Investigate whether established occupational guidelines protect the worker from injurious short-term effects, and

3. Offer considerations to mitigate adverse WBV effects
What is whole-body vibration (WBV)?

- Mechanical oscillations of any frequency are transferred to the body.
- Shakes, bumps, and jolts

<table>
<thead>
<tr>
<th>WBV Parameters</th>
<th>WBV Training and Rehabilitation</th>
<th>Occupational WBV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route of Transmission</td>
<td>Feet</td>
<td>Ischial tuberosity</td>
</tr>
<tr>
<td>Duration</td>
<td>~ 5 min</td>
<td>6-8 hours</td>
</tr>
<tr>
<td>Frequency</td>
<td>45 Hz</td>
<td>0-20 Hz</td>
</tr>
<tr>
<td>Intensity</td>
<td>Varies</td>
<td>Varies</td>
</tr>
<tr>
<td>Direction</td>
<td>All directions</td>
<td>All directions</td>
</tr>
</tbody>
</table>
### Equipment and Equipment Categories

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Weighted RMS Acceleration (m/s²)</th>
<th>VDV (m/s^{1.75})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td><strong>Bulldozer</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large (9)</td>
<td>0.92</td>
<td>0.14</td>
</tr>
<tr>
<td>Small (4)</td>
<td>1.11</td>
<td>0.35</td>
</tr>
<tr>
<td><strong>Excavator</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(14)</td>
<td>0.51</td>
<td>0.28</td>
</tr>
<tr>
<td><strong>Scraper</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4)</td>
<td>1.61</td>
<td>0.30</td>
</tr>
<tr>
<td><strong>Grader</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4)</td>
<td>0.55</td>
<td>0.15</td>
</tr>
<tr>
<td><strong>Skid steer vehicle</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mini (3)</td>
<td>1.22</td>
<td>0.48</td>
</tr>
<tr>
<td>Regular (3)</td>
<td>1.18</td>
<td>0.63</td>
</tr>
<tr>
<td><strong>Backhoe</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3)</td>
<td>1.05</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Compactors</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compactor (3)</td>
<td>0.91</td>
<td>0.41</td>
</tr>
<tr>
<td>Vibratory compactor (5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Crawler loader</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3)</td>
<td>1.01</td>
<td>0.18</td>
</tr>
<tr>
<td>Wheel loader (2)</td>
<td>1.16</td>
<td>0.70</td>
</tr>
<tr>
<td><strong>Mobile crane</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2)</td>
<td>0.15</td>
<td>0.07</td>
</tr>
<tr>
<td><strong>Off-road dump truck</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2)</td>
<td>1.21</td>
<td>0.70</td>
</tr>
</tbody>
</table>

*Insufficient data to calculate range and standard deviations due to only one test score.

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**EU Good Practice Guide, 2006**

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*EU Good Practice Guide, 2006*

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*CRE-MSD Centre for Research on the Prevention of Musculoskeletal Disorders*

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*University of Waterloo School of Medicine*

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*Washington University in St. Louis*

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*SHRF Saskatchewan Health Research Foundation*
Health problems associated with WBV:

• Neck problems
• Hearing loss
• Gastrointestinal tract problems
• Spinal degeneration
• Low back pain
WBV and Low Back Pain

• Strong epidemiological evidence linking WBV and low back pain

• Dose-response relationship is seen between WBV and driving-related LBP (Tiemessen, 2008)

• Healthy professional drivers with regular daily vibration exposure are at risk of developing low back symptoms over a two-year follow-up period (Bovenzi, 2010)
WBV $\rightarrow$ LBP $\rightarrow$ Sleep Disturbance Link?

• Systematic review: chronic LBP is associated with sleep disturbances. (Kelly et al., 2011)

• Meta-analysis: 58.7% prevalence of sleep disorders for people with non-specific LBP (Alsaadi et al., 2011)

• Bidirectional relationship
More direct and acute relationship?

WBV

Low Back Pain

Sleep Disturbances

Alertness
Acute effects of WBV and alertness

Lab Studies - instrumented measures

• Decreased wakefulness - EEG (Satou et al. 2006; Satou et al. 2007; Azizan & Fard, 2014)

• Increased reaction times and vigilance lapses (Wang & Johnson 2014)

Lab Studies - self-reports

• Conflicted results with self-reported alertness after acute exposures to WBV (Ljunberg, 2010)
Prevalence of Truck Driver Drowsiness

MaCartt et al. 2000 (n=593)
• 47% have fallen asleep at the wheel
• 25% have done so in the past year

Castro et al. 2004 (n=238)
• 56% are tired at least some of the time while driving
• 32% have driven with their eyes closed
In Canada, driver fatigue accounts for 1.5% of heavy vehicle collisions.

(National Collision Database, 2003-2008)
Factors affecting Driver Fatigue

- **Driver Factors**
  - Time of day
  - Sleep duration
  - Sleep quality
  - Health
  - Lifestyle
  - Medication
  - Caffeine

- **Operational Factors**
  - Task complexity
  - Task monotony
  - Time on task
  - Rotational shiftwork
  - Workplace culture
  - Rest breaks

- **Environmental Factors**
  - Weather
  - Road conditions
  - Seasonal variation
  - Cabin design
  - Lighting
  - Temperature
  - Air quality
  - Noise
  - **Vibration**

(Modified from Moscovitch et al. 2006; May & Baldwin 2009)
Electromagnetically Active Vibration-Cancelling (EVAC)
Study Objectives

1. Determine if an EAVC seat intervention affects vigilance over the course of a workday, and a workweek

2. Determine if drivers find the EAVC seat comfortable.
Repeated measures crossover design (n=5)

<table>
<thead>
<tr>
<th></th>
<th>Existing Seat</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>EAVC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Shift</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>PVT and Questionnaire</td>
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<tr>
<td>Work Shift</td>
<td>WBV Measurement</td>
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<td></td>
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<tr>
<td>Seat Installation</td>
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<td></td>
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<tr>
<td>Post-Shift</td>
<td>PVT and Questionnaire</td>
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</tbody>
</table>

Methods:
Independent Variables

1. Seat Type

2. Time of Day

3. Day of Workweek
Whole-body Vibration (WBV)
1. $A(8) \text{ (m/s}^2\text{)}$

Psychomotor Vigilance Task (PVT)
1. Mean response time (RT)
2. Fastest 10% RT
3. Slowest 10% RT
4. Variability
5. Reaction speed (1/RT)
6. Number of Lapses (>500ms)

10-point pain scale
1. Shoulder(s)
2. Wrist(s)/Forearm(s)
3. Knee(s)
4. Ankle(s)/Feet
5. Neck
6. Upper Back
7. Lower Back
8. Buttocks/Legs
## Demographics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mean</th>
<th>SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs.)</td>
<td>54.4</td>
<td>8.35</td>
<td>(43 - 64)</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.73</td>
<td>0.10</td>
<td>(1.57 - 1.83)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>108</td>
<td>27.01</td>
<td>(79-140)</td>
</tr>
<tr>
<td>Body mass index</td>
<td>35.8</td>
<td>7.67</td>
<td>(27.3 - 44.6)</td>
</tr>
<tr>
<td>Time in trucking industry (yrs.)</td>
<td>23.9</td>
<td>13.74</td>
<td>(16 - 44)</td>
</tr>
<tr>
<td>Time with company (yrs.)</td>
<td>4.2</td>
<td>4.87</td>
<td>(1.33 - 12.83)</td>
</tr>
<tr>
<td>Hours of work per week</td>
<td>57</td>
<td>7.58</td>
<td>(45 - 65)</td>
</tr>
<tr>
<td>Hours of driving per week</td>
<td>46.5</td>
<td>7.83</td>
<td>(40 - 60)</td>
</tr>
</tbody>
</table>
## Characteristics of the Workday

<table>
<thead>
<tr>
<th>Work Characteristic</th>
<th>Seat Type</th>
<th>Mean</th>
<th>SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sleep Duration</strong></td>
<td>Existing</td>
<td>7h 16m</td>
<td>43m</td>
<td>6h 26m - 8h 09m</td>
</tr>
<tr>
<td></td>
<td>EAVC</td>
<td>7h 15m</td>
<td>49m</td>
<td>6h 30m - 8h 16m</td>
</tr>
<tr>
<td><strong>Time on Task</strong></td>
<td>Existing</td>
<td>9h 44m</td>
<td>1h 08m</td>
<td>8h 29m – 11h 16m</td>
</tr>
<tr>
<td></td>
<td>EAVC</td>
<td>10h 11m</td>
<td>1h 12m</td>
<td>9h 05m - 12h 10m</td>
</tr>
<tr>
<td><strong>Distance (km)</strong></td>
<td>Existing</td>
<td>669</td>
<td>188</td>
<td>341 - 822</td>
</tr>
<tr>
<td></td>
<td>EAVC</td>
<td>662</td>
<td>136</td>
<td>431 - 766</td>
</tr>
<tr>
<td><strong># of Caffeinated Beverages/shift</strong></td>
<td>Existing</td>
<td>1</td>
<td>2</td>
<td>0 - 4</td>
</tr>
<tr>
<td></td>
<td>EAVC</td>
<td>1</td>
<td>2</td>
<td>0 - 4</td>
</tr>
<tr>
<td><strong># of Coffee/shift</strong></td>
<td>Existing</td>
<td>1</td>
<td>2</td>
<td>0 - 4</td>
</tr>
<tr>
<td></td>
<td>EAVC</td>
<td>1</td>
<td>2</td>
<td>0 - 4</td>
</tr>
<tr>
<td><strong># of Energy Drinks/shift</strong></td>
<td>Existing</td>
<td>0</td>
<td>0</td>
<td>0 - 1</td>
</tr>
<tr>
<td></td>
<td>EAVC</td>
<td>0</td>
<td>0</td>
<td>0 - 0</td>
</tr>
<tr>
<td><strong># of Soda/shift</strong></td>
<td>Existing</td>
<td>0</td>
<td>0</td>
<td>0 - 1</td>
</tr>
<tr>
<td></td>
<td>EAVC</td>
<td>0</td>
<td>0</td>
<td>0 - 1</td>
</tr>
<tr>
<td><strong># of Tea/shift</strong></td>
<td>Existing</td>
<td>0</td>
<td>0</td>
<td>0 - 1</td>
</tr>
<tr>
<td></td>
<td>EAVC</td>
<td>0</td>
<td>0</td>
<td>0 - 1</td>
</tr>
</tbody>
</table>
WBV Attenuation

<table>
<thead>
<tr>
<th></th>
<th>RMS m/s²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor</td>
<td>0.5</td>
</tr>
<tr>
<td>Existing</td>
<td>0.5</td>
</tr>
<tr>
<td>EAVC</td>
<td>0.2</td>
</tr>
</tbody>
</table>

EAV
Change in PVT Over Workday

- **Mean RT:** p = .047

<table>
<thead>
<tr>
<th>Time of Day</th>
<th>Slowest 10% RT</th>
<th>Fastest 10% RT: p = .02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Shift</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-Shift</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time of Day</th>
<th>Number of Lapses</th>
<th>Mean RT: p = .047</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Shift</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-Shift</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time of Day</th>
<th>Response Speed (1/RT)</th>
<th>Variability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Shift</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-Shift</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Change in PVT Over Workday**
Change in PVT Over Workweek

Response Times (ms)

Day of Workweek

Slowest 10% RT

Fastest 10% RT

Variability

Number of Lapses

Day of Workweek

Response Speed (1/RT)

Day of Workweek

Mean RT: $p = .052$

Reaction Speed: $p = .074$

Existing

EAVC
Change in Discomfort over Workday

0 = no pain; 10 = Worst pain Imaginable

Time of day

Lower Back
P<.01

Wrist(s)/Forearm(s)
p=.012
Summary

The seating intervention that reduced in WBV →

1. Reductions in the decrements PVT performance over a workday
2. Reductions in the decrements of PVT performance over a workweek (trend)
3. Reductions in the development of discomfort in the low back and wrist(s)/forearm(s) over a workday
Replication Study

n=11 drivers; 11 hour shifts; mean age = 52.3
EVAC = 0.27 m/s² vs. Passive = 0.54 m/s²

(Wang et al., 7th American Conference on Human Vibration - 2018)
Limitations

• Low sample size
• PVT cannot be assessed while driving
• No randomization or blinding of conditions
WBV Guidelines for (Long-Term) Health and Safety of Workers

- International Guides and Standards
  - Measurement
  - Evaluation
  - Assessment
- British Standard 6841 (1987)
- European Union Directive 2002/44/EC
WBV Guidelines

• Exposure Action Value (EAV)
  • If EAV exceeded, the employer shall establish and implement a programme to reduce to a minimum exposure (8hr reference: 0.5 ms\(^{-2}\) r.m.s.)

• Exposure Limit Value (ELV)
  • If ELV exceeded, the employer shall take immediate action to reduce exposure below ELV (8hr reference: 1.15 ms\(^{-2}\) r.m.s.)

• Mechanical Shock
  • Transient force, short duration and high amplitude
  • Crest factors > 9 (ratio of highest impact magnitude to weighted r.m.s. - ISO 2631-1).
  • EAV: 9.1 m/s\(^{1.75}\)
  • ELV: 21 m/s\(^{1.75}\)
WBV Acute Effects and Guidelines?

• No current guidelines for potential acute effects from WBV
• There are several gaps in applying existing knowledge of possible WBV acute effects:
  • Responses from deterministic oscillatory motion
  • Occupationally relevant?
  • Single system/domain effects
  • Few laboratory-controlled experimental studies
Study Objectives

1. Is there an effect of 60-minutes of WBV exposure at four different vibration intensities? (Pre vs. Post)

2. Are there differences in effects between WBV intensities? (Based on EU Directive Guidelines)
Study Methods

- 18 healthy participants (9M; 9F)
  - 26.1 years ± 5.3; 1.73 meters ± 0.09; 67.6 kilograms ± 10.8
- 4 conditions on 4 separate days at least 24 hrs apart, randomized
- Simulated signals based on field data from ATV agricultural herding work
- Vibration intensity standardized to estimated total daily WBV exposure of 2.43 hrs (Clay et al., 2015)
- Participant weight-adjusted
<table>
<thead>
<tr>
<th>Condition</th>
<th>Acceleration</th>
<th>Impact Description</th>
<th>CF</th>
<th>VDV Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiet Sitting</td>
<td>EAV*</td>
<td>0.938 m/s² RMS (SD = 0.06)</td>
<td>10.46 CF</td>
<td>13.49 m/s¹⁷⁵ VDV (SD = 5.19)</td>
</tr>
<tr>
<td></td>
<td>EAV + Transient impact</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ELV*</td>
<td>2.129 m/s² RMS (SD = 0.06)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

60 minutes exposure
Standardized television programming to mitigate boredom
Noise cancellation headphones
Hands on handlebars, feet on platform surface
5 Hz along Z-axis
Study Methods - Measurement

• Test battery pre- and post-condition
• Nine cognitive and sensorimotor indices or measures
• Example:
  – Rating of Perceived Headache/Discomfort (10 cm VAS)
Rating of Headache/Discomfort

![Graph showing VAS Rating (0-100) for different conditions: Control, Low, Shock, High. The graph compares pre and post conditions with error bars indicating variability.](#)
Pre & Post Difference p<0.05
Headache/Discomfort: Low, High
Blink Frequency: Low
PVT Time: High
PVT Errors: High
Postural Sway: Low, High

Rating of Headache/Discomfort

Postural Sway

Blink Frequency

PVT Errors

PVT Reaction Time

King Devick Time
- Pre
- Control Post
- Low Post
- Shock Post
- High Post

King Devick Errors
Pre & Post Difference p<0.008
Composite: All
Arm: All
Shoulder: All
Neck: Low, Shock, High
Upper Back: All
Lower Back: All
Buttock: All
Thigh: Low, Shock, High
Knee: Shock, High
Calf: High
Ankle: Shock, High

Control Post
Low Post
Shock Post
High Post
Summary

• **Control**: Upper body discomfort
• **Low**: Upper body discomfort, Headache/discomfort, postural imbalance, effect on cognitive functioning less clear
• **Shock**: Whole body discomfort but no significant effects in remaining variables (stiff vs. floppy postural adjustment strategies to sudden perturbation)
• **High**: Whole body discomfort, Headache/discomfort, postural imbalance, decrements in vigilance.
Summary

• WBV did not induce additional effects beyond those seen for sitting without vibration.
• WBV is not necessarily the only source of acute sensorimotor or cognitive effects.
• However, pre-post effect increased with increasing vibration intensity.
• *Quantitative guidance is insufficient to identify vibration hazards but qualitative guidance (i.e., reduce the risk to a minimum) is the key message* (Griffin, 2003)
Hierarchy of Controls

- **Elimination**: Physically remove the hazard
- **Substitution**: Replace the hazard
- **Engineering Controls**: Isolate people from the hazard
- **Administrative Controls**: Change the way people work
- **PPE**: Protect the worker with Personal Protective Equipment

Most effective

Least effective
Risk Mitigation and Interventions

- Active suspension seats are effective
  - But expensive
  - Doesn’t address prolonged sitting

- Work-Scheduling/Arrangement
  - Discretionary
  - Non-routine type of work

Publications of Interest:

