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The effects of a new seat suspension system on whole body vibration exposure and driver low back pain and disability: results from a randomized controlled trial in truck drivers

Jack T. Dennerlein[1], **Jennifer M. Cavallari**[2], **Jeong Ho (Jay) Kim**[3], **Nicholas H. Green**[1]

[1]Department of Physical Therapy, Movement, and Rehabilitation Sciences, Bouvé College of Health Sciences, Northeastern University, Boston, MA USA

[2]Department of Public Health Sciences, University of Connecticut School of Medicine, Farmington, CT USA

[3]Environmental and Occupational Health Program, School of Biological and Population Health Sciences, Oregon State University, Corvallis, OR, USA

Abstract

Through a randomized controlled trial, we evaluated the effects of an electro-magnetic active seat suspension that reduces exposure of a long-haul truck driver to whole body vibration (WBV) on low back pain (LBP) and disability. Among 276 drivers recruited from six trucking terminals of a major US trucking company, 135 eligible drivers were assigned to either having an Active Seat (Intervention: n=70) – the BoseRide® electro-magnetic active seat – or Passive Seat (reference: n=65) – a new version of their current seat (passive air suspension seat) – installed in their truck via block (terminal) randomization. Low back pain (LBP in 0–10 scale) and the Oswestry LBP Disability Index were collected before and 3-, 6-, 12-, 18-, and 24-months post seat installation. LBP and LBP disability scores were significantly lower post seat installation in both groups. At 3 months, LBP decreased −1.3 [95% CI: −0.8 - −2.1: n= 46] for drivers in the Active Seat arm, and −1.5 [95% CI: −0.9 - −2.0: n = 41] for drivers in the Passive Seat arm. In a subset of drivers, WBV exposures were collected before and after the seat installation. WBV exposures significantly decreased post seat installation for Active Seat ($p<0.01$) but not for Passive Seat ($p=0.15$). While the new seat-suspension technology reduced WBV exposures, LBP appeared to be improved by multiple factors. These results were limited by the secondary prevention approach and the longer-term loss to follow up due to large rates of driver turnover typical for the industry.

INTRODUCTION

Truck drivers have a high prevalence of musculoskeletal disorders (MSDs), especially low back pain (LBP) (Davis, Dunning, Jewell, & Lockey, 2014; Rauser et al., 2008; Smith & Williams, 2014). In a two-year longitudinal study of truck drivers, the incidence of new LBP cases was 36 percent (Bovenzi, 2010). In the state of Washington from 2006 to 2012, strains, sprains, and overexertion injuries accounted for over one-third of workers' compensation

Corresponding Author: Jack T. Dennerlein, Department of Physical Therapy, Movement, and Rehabilitation Sciences, Robinson Hall, Room 301, Northeastern University, 360 Huntington Avenue, Boston, MA 02115, +1 617 373 5428, j.dennerlein@northeastern.edu.

claims among truck drivers (Rauser, Smith, & Williams, 2014). In the US overall, LBP accounts for 20% of workers' compensation claims and over a one-third of costs (Leigh, 2011; Webster & Snook, 1994). In 2019 in the US, MSDs of the back accounted for 33% of occupational related MSDs and 11% of all occupational non-fatal injuries, measured by days away from work (BLS, 2021). LBP can lead to long-term disability, which creates substantial economic burden and loss of productivity in the workplace (Punnett et al., 2005).

Exposure to whole body vibration (WBV) while driving is a major physical risk factor associated with the high prevalence of musculoskeletal disorders among professional drivers (Bovenzi, Schust, & Mauro, 2017; Burstrom, Nilsson, & Wahlstrom, 2015; Teschke, 1999). Numerous studies have documented strong associations and dose-response relationships between LBP and exposure to WBV in professional drivers (Bernard, 1997; Bovenzi, 2005, 2009; Bovenzi & Schust, 2021; Pope & Hansson, 1992).

For several decades, the standard approach to reducing truck drivers' exposure to WBV has been the installation of passive pneumatic seat suspension systems; however, this approach has had limited success in reducing exposure to WBV (Kim et al., 2016). Passive systems have a fixed frequency response targeting oscillatory components of WBV exposure with frequencies between one to six Hz. However, the typical impulsive type of vibrations includes frequencies up to 30 Hz, which can excite the resonate frequencies of the passive system (Blood, Yost, Camp, & Ching, 2015). Therefore, the passive suspension seats are ineffective in reducing WBV exposure and in some cases can amplify the vibration exposure at the seat in some circumstances (Kim et al., 2016; Thamsuwan, Blood, Ching, Boyle, & Johnson, 2013).

New seat suspension technology that actively measures and then compensates for vibrations measured at the floor through electro-magnetic actuators appears to reduce WBV exposure compared to the current industry passive suspension seats by as much as 50% (Blood, Dennerlein, Lewis, Rynell, & Johnson, 2011; Johnson, Zigman, Ibbotson, Dennerlein, & Kim, 2018). This new seat suspension with active-electromagnetic technology uses accelerometers mounted at the base of the seat's suspension to measure vibrations transmitted from the truck. An algorithm based on dynamic controls theory then drives a high response linear actuator integrated in the suspension to attenuate the transmission of the vibration from the floor to the seat pan and the driver's exposure to WBV. Due to the high fidelity in the frequency response, this active suspension is considerably more successful in reducing these exposures than the standard approach of passive seat suspension systems (Blood et al., 2011; Johnson et al., 2018).

Our previous pilot study demonstrated promising effects of improving health outcomes, including LBP and related disability of drivers in a single geographical region. However, its small sample size (i.e., insufficient statistical power) resulted in lack of statistical significance in all of the health outcomes. In addition, due to substantial dropouts, the follow-up period of this longitudinal study was only up to six months (Kim, Zigman, Dennerlein, & Johnson, 2018). To overcome these limitations, the goal of this longitudinal (24-month) randomized controlled trial was to evaluate the impact of reducing WBV exposures using an active-electromechanical seat suspension system on professional drivers' musculoskeletal health outcomes, mainly pain and functional limitations associated with LBP. To achieve this study goal, we tested the main hypothesis that drivers who received the intervention seat (the new electro-magnetic active seat) would experience larger improvements in musculoskeletal pain and associated functional limitations during the follow up periods (time) compared to drivers who receive the reference seat (the industry standard pneumatic suspension passive seat).

METHODS

Study Design

The study was a longitudinal randomized controlled trial (RCT) with two study arms: the intervention group (Active Seat) who received the BoseRide® electro-magnetic active suspension seat and the reference group (Passive Seat) who received a new version of their current seat (industry standard passive suspension seat). Before assigning drivers to the intervention or reference group, we implemented cross-sectional baseline driver surveys to collect demographics, eligibility criteria information, working history, and health outcome measures. Eligible drivers were assigned into the two groups via block (truck terminal) randomization. The participants were followed for 24 months after seat installation for post-intervention measurements at 3, 6, 12, 18, and 24 months. To confirm that WBV exposures were reduced in the Active Seat arm and did not change in the Passive Seat arm, we completed WBV exposure assessments in a subset of drivers at baseline, immediately after seat installation, and at 12 and 24 months after seat installation. All protocols, procedures, surveys, and consent forms were approved by the Northeastern University Committee for Human Subjects Research.

Participants and the Intervention

Professional drivers were recruited from six terminals of a national trucking company. At study initiation, the company had over three dozen terminals and over 10,000 drivers in the United States. These six terminals were in industrial parks near urban areas in Oregon, California, Texas, Arkansas, North Carolina, and Indiana. They were chosen in consultation with the company based on several feasibility factors, including large numbers of eligible drivers, facilities to support the seat installation, and a full and established staff to support the research activities. In-person, face-to-face recruitment occurred during a two-week on-site visit by at least two research staff.

During the two-week recruitment periods, drivers were invited to meet with researchers via printed flyers, and placards placed in the driver common areas of a terminal, as well as through in-cab communications from their dispatchers. The researchers were based in a central location, usually in the lunchroom. Of the drivers who met with or were engaged by the researchers, those who expressed interest in study participation were invited to complete a baseline survey once and then weekly pain surveys for four weeks.

Eligibility criteria for the drivers were a minimum tenure of one year with the company; assigned to a single truck (not a slip seater) that is less than four years old; 18–60 years of age; log a minimum driving time of 20 hours per week; perform no manual material handling as part of their work duties (not involved in loading and unloading of the truck's cargo); and exhibit LBP. To meet the eligibility criteria of existing LBP, drivers had to report LBP on the baseline survey within the last week (having 1 or greater on a 0–10 scale) or report at least one episode of LBP in the last three months. In addition, eligible drivers had to complete three of the four weekly surveys prior to seat installation. Drivers with a history of back surgery were excluded.

Eligible drivers were assigned to either Active Seat (the intervention group) or Passive Seat (reference group) via block randomization at each of the six terminals (Altman & Bland, 1999). Once assigned to a seat, the drivers were scheduled for seat installation at their terminals during a two-week period six to eight weeks after the recruitment visit. Seats were installed by on-site technicians employed by the trucking company.

The Active Seat was a *BoseRide®* electro-magnetic suspension seat (Bose Corporation, Framingham, Massachusetts, USA) that measures the acceleration of the suspension base and then signals the suspension's actuators to reduce the vibration reaching the seat and driver. The Passive Seat was a passive suspension seat (National 2000, National Seating, Franklin, Tennessee, USA), with a passive pneumatic (spring and damper) suspension system. The Passive Seat is the industry standard and was the original equipment manufacturer for the Freightliner Trucks utilized in the trucking company's fleet. Hence, Passive Seat drivers received a brand-new version of their current seat. In an attempt to conceal the type of seat each driver received, all visible brand and model information labels were removed from each seat. Because of the different technical requirements of the seats, blinding of the research staff was not possible.

Drivers in both groups received training on how to adjust the seats according to ergonomic guidelines developed by an ergonomic consulting company used by the trucking company. Both groups received "glove-box" cards reminding them of the adjustments and study contact information.

Measurements

The primary health outcomes were LBP severity, overall musculoskeletal pain severity, and LBP disability. These driver outcomes were measured via electronic self-administrated surveys at the time of recruitment (baseline), 3-, 6-, 12-, 18-, and 24-months post seat installation (follow up). To capture the episodic nature of pain, LBP and overall musculoskeletal pain severity were captured via weekly surveys for four weeks before seat installation and for twelve weeks (three months) after seat installation.

The drivers completed surveys electronically through their in-cab communication unit, a mobile computing device (smart phone/tablet) or desktop computer at the terminal. For the weekly and follow-up surveys, research staff notified drivers to complete surveys by corresponding with the drivers' dispatchers. Researchers followed up with their dispatchers when the drivers did not respond, requesting that they complete the survey.

On all surveys, LBP severity was assessed by a single question asking the drivers to rate their LBP in the past seven days at its highest or worst level. The single question was a visual analog scale ranging from 0 to 10 with verbal anchors at 0 (no pain) and 10 (worst pain you can imagine). Overall musculoskeletal pain during the past seven days was assessed in seven body areas using the same response scale. The body areas included the low back; neck; shoulders; wrists and forearms; legs (sciatica); knees; and ankles and feet. Overall pain was scored by the summation of the responses of these seven items (0 to 70) (Amick et al., 2003).

LBP functional limitation was assessed for the baseline and follow up surveys using the Oswestry Disability Index (Fairbank, Couper, Davies, & O'Brien, 1980; Fairbank & Pynsent, 2000). The Index contains ten items assessing the impact of back pain on activities of daily life. Scoring ranges from 0 (no disability) to 100 (completely disabled) (Vianin, 2008).

The baseline survey included questions about a driver's experience with back pain in the past three months, specifically the number of episodes of LBP and the duration of these episodes (Johanning, 2011). The baseline survey also collected driver demographics — gender, age, company tenure, education, and job title. In addition, the survey included the 12-item Short From (SF-12) survey to evaluate drivers' overall health relative to the US population (Ware, Kosinski, & Keller, 1996).

To confirm changes in WBV exposures, we measured WBV in a subset of drivers before (usually during recruitment visits) and after seat installation (one-week, 12- and 24-month post seat installation). Drivers who completed the baseline survey and were available for measurements while research staff were on site were invited to participate in the vibration measurements. For the first 30–40 miles of the drivers' regular routes, raw unweighted-acceleration data were collected at 1,280 Hz using either a four or eight channel data recorder (DA20 or DA-40; Rion Co. LTD; Tokyo, Japan) and tri-axial seat-pad accelerometers (356B40; PCB Piezotronics; Depew, NY) mounted on the seats according to the International Organization for Standardization (ISO) 2631–1 standards. Research team members coordinated with the drivers to meet at a roadside location some 30 to 40 miles from the terminal to retrieve the instrumentation providing 60 to 90 minutes of continuous raw acceleration data.

The raw acceleration data were processed via international WBV standards ((ISO), 1997, 2004). The ISO WBV exposure parameters were the root mean square weighted average vibration (A) and the vibration dose value (VDV), with the former capturing the overall average of the exposure and the latter capturing the more impulsive components (Marin et al., 2017). These parameters calculated were normalized to reflect eight hours of exposure: A(8) and VDV(8).

Data Analyses

Based on power analysis and anticipated loss to follow-up due to high rates of driver turnover in the industry, we aimed to recruit 70 drivers per arm of the study. The proposed sample size was based on power calculations on an estimated LBP severity score for those who report mild symptoms or higher of 2.8 (SD 0.8; scale of 1–5) collected from an unpublished survey of truck drivers from the Washington State Department of Labor and

Industries (Silverstein, 2010). For type I error of 5%, we would need a total of 50 subjects (25 each arm) to have 80% power to detect a mean pain score change of 25% in the mean baseline value assuming no change in the reference group. To account for loss to follow-up due to high turnover in the industry (>50% per year), we set our goal for a total of 140 drivers, 70 per arm, which assumed that for the second year the loss to follow up would be much smaller reflecting the smaller turnover rate for drivers with tenure of over 12 months.

The success of randomization was checked by testing for differences in baseline demographics and outcome measures between the groups using two sample t-tests for continuous variables and chi-square tests of r categorical values. These tests were also performed to determine if differences existed between those lost to follow-up and those who remained in the study.

To confirm that WBV exposure metrics decreased after seat installation in the Active Seat and no reduction occurred for the Passive Seat, we completed two one-way analyses of variance ANOVAs, one for each arm (Active Seats and Passive Seats) with time as the independent variable and the A(8) and VDV(8) values for the z-axis as the dependent variable. Dunnett Least Square Means post-hoc tests compared the metrics measured at follow-up with the values measured at baseline. Two sample student t-tests examined if differences existed between the two arms for these metrics at each point of time. In addition, a two-way ANOVA that included time, seat, and a time-and-seat interaction was completed to confirm the results of the one-way ANOVA.

Pre-post differences in LBP severity, overall pain, and Oswestry Index values between baseline surveys and follow-up were calculated for each participant who had follow up data. The mean and its 95 percent confidence intervals (95% CI) were calculated for the drivers within each arm. Significance was determined when the 95% CI did not include zero – indicating significant change. The pre-post outcome differences at each time point were compared between each arm (Active Seats and Passive Seats) using two-sample student t-tests. In addition, mixed effect regression models were used to confirm differences in pain over time for the two arms. Fixed effects included time, an interaction term of seat by time, participant age, and participant BMI. A random intercept, slope and unstructured covariance was used to account for the repeated measures over time. Regression models were applied to the three dependent variables: LBP, overall pain, and values of the Oswestry Index. Significance was defined at $\alpha = 0.05$ for all statistical tests.

RESULTS

Of the 276 drivers who agreed to participate at the six terminals, 135 completed the eligibility requirements and were allocated Active Seat or Passive Seat via block (terminal) randomization (Figure 1). Reasons for ineligibility included stopped working at the company (n=22); did not complete the baseline or weekly surveys (n=109); did not have LBP (n=4); or were terminated, on leave during allocation, or other administrative reasons (n=5). There were no significant differences in the baseline demographics between the groups (Active Seat and Passive Seat) (Table 1). Immediately after allocation, three drivers rejected the Active Seat and one rejected the Passive Seat, requesting their original seats be re-installed.

For the full 24 months, loss to follow-up was large, with 86 drivers dropping out. A majority (51) dropped out because of change in employment status (terminated, quit, or transferred to another division). Other reasons included medical and disability leave, change in equipment, or rejecting their new seat as described above. During follow up, survey response rates of eligible drivers were well above 65% except for at the 24-month follow up where the response rate in Active Seat drivers was 57%. There were no statistically significant differences in demographics and outcome variables in those who remained in the study and responded to the surveys compared to those who dropped out or did not respond to the surveys. In addition, there were no statistically significant differences in the demographics and outcome variables in the subset of drivers with WBV measures compared to those without measurements.

WBV exposure metrics decreased significantly post seat installation for Active Seat drivers, whereas for Passive Seat drivers the small (<10%) decreases were not significant (Table 2). Baseline WBV exposure metrics did not show any differences between the two arms. However, Active Seat drivers had significantly lower WBV metrics than the Passive Seat drivers after the seat installation at post-intervention, 12- and 24-month follow up points (Table 2).

Low back and overall pain scores were significantly lower post seat installation for all drivers allocated a new seat, except for at 24-months among drivers who received the Active Seat (Tables 3 and 4). The mixed model regressions demonstrated a significant effect of time (pre-post intervention) for both LBP ($p = 0.03$) and overall pain severity ($p<0.01$); however, there was no significant interaction effect between time and seat for LBP scores ($p = 0.84$) and overall pain scores ($p = 0.20$) when accounting for driver age and BMI.

Oswestry LBP disability scores improved post seat installation in both groups, albeit not as consistently as the pain severity scores (Table 5). When accounting for driver age and BMI, the mixed model regressions demonstrated a significant effect of time ($p <0.01$); however, there was no significant interaction effect between time and seat ($p = 0.28$).

DISCUSSION

The goal of this study was to determine the impact of reducing WBV exposures through an electro-magnetic suspension seat on LBP and functional limitations in long-haul truck drivers. The exposure assessment confirmed that the electro-magnetic suspension seat (Active Seat) more effectively reduced WBV exposures than the industry standard passive suspension (Passive Seat) as observed before (Blood et al., 2011; Johnson et al., 2018). Despite the differences in the reduction of WBV between the groups, similar significant reductions in pain scores post seat installation were observed in both the intervention (Active Seat) and reference (Passive Seat) groups. In terms of disability, the improvements observed in the Active Seat drivers were larger for all follow up times except at 6-months – however, the differences between the groups were not statistically significant. While there was a positive effect, the results do not support the hypothesis that drivers who receive seats with the electro-magnetic active suspension (Active Seat) will experience greater reductions in pain and disability than those who receive the passive pneumatic suspension seat (Passive Seat).

The improvement of pain scores in the Passive Seat drivers was not expected, especially given there were no differences in WBV exposure metric over time and the newly installed seats had the same seat suspension systems as the seats in the trucks prior to the intervention. These results are in contrast to our assumptions for the power studies and our pilot study results. Our sample sized calculation had presumed there would be no changes in outcome measures in the Passive Seat drivers. The pilot showed greater pain improvements with Active Seat drivers compared to Passive Seat drivers (Johnson et al., 2018; Kim, Zigman, et al., 2018). Unlike the pilot study, drivers in both arms received specific training and coaching to adjust their seats based on recommendations from an ergonomic consultant used by the trucking company. As previous studies have shown, a driver's posture significantly affected the transmissibility of WBV exposure (Jack & Eger, 2008; Raffler et al., 2017; Rahmatalla et al., 2008; Zimmermann & Cook, 1997); the ergonomic training on the seat adjustment may have reduced awkward driving postures and risk for LBP. This is in line with previous study findings in non-driving settings showing seat adjustments, along with training, can collectively reduce musculoskeletal pain outcomes (Robertson, Ciriello, & Garabet, 2013; Van Eerd et al., 2016). Professional driving poses multiple risk factors for musculoskeletal pain, including the sedentary nature of driving (prolonged sitting), awkward driving postures, and other factors we did not measure (NRC/IOM, 2001). Another explanation may be a Hawthorne effect (McCarney et al., 2007). If true, one would expect the Hawthorne effect to be present during the period prior to seat installation; however, the pre-seat installation weekly pain scores were similar to baseline values, suggesting more of a placebo effect. In agreement with the placebo effect, a few Passive Seat drivers did report to us that they liked the improvements of the new seat that they received.

The larger improvements of the Oswestry disability scores in the intervention group (Active Seat) were promising. Based on previous studies showing that minimal clinically important changes range from 4 to 16 percentage points (Lauridsen, Hartvigsen, Manniche, Korsholm, & Grunnet-Nilsson, 2006), the intervention group experienced clinically important improvement (reduction) in low back disability, especially at 12 and 18 months. Functional limitations often have better predictive behavior surrounding clinical hypotheses and may be better measures of health impacts of interventions (Amick et al., 2004; Dennerlein et al., 2002; Katz et al., 1997; Lerner et al., 2001). In addition, disability is often easier to prevent and impact than pain itself (Snook, 2004). With that said, the Oswestry disability index is often used for clinical populations, and the drivers' disability scores were small (in the 0–20 range, out of a possible 0–100 range of scores). Most drivers were classified as experiencing "minimal disability" (Fairbank & Pynsent, 2000). As such, these drivers could only have experienced a small improvement in their scores, reducing the power to detect change. The effects of reducing WBV exposure may have been greater for those with higher disability scores, allowing those with more severe LBP to remain at work; however, such hypotheses need further investigation.

As observed before, exposure to WBV did decrease as expected in the subset of drivers in the Active Seat group, while little change in WBV were observed in the subset of drivers in the Passive Seat group (Blood et al., 2015; Johnson et al., 2018; Kim, Marin, & Dennerlein, 2018; Kim, Zigman, et al., 2018). This result is consistent with previous studies showing superior attenuation performance of Active Seats in various vehicles compared to Passive Seats. Due to far greater fidelity in frequency response, this electro-magnetic active suspension seat (Active Seat) has shown greater efficacy in attenuating vibration for a wide range of frequency in various driving conditions. However, as a passive seat suspension system (Passive Seat) has a fixed dynamic range, it is not capable of changing its response with changing road conditions and their associated vibration frequency ranges.

While the terminals and routes differed across drivers, each WBV exposure measurement included a similar robust set of road conditions. These included both paved and unpaved surfaces in terminal truck yards, the surrounding paved neighborhood streets and regional roads with speed humps, and interstate highways traveling approximately 30 to 40 miles before meeting a researcher to retrieve the measurement equipment.

These WBV exposure measurements were limited to a subset of drivers due to feasibility issues associated with measuring all drivers, a limited number of accelerometers and data recorders, limited time of staff on site, and coordination with drivers and their driving routes. The subset also experienced a high dropout rate and were not fully repeated measures, which reduces the power to test for differences. Despite the non-randomly drawn subset, the WBV exposure level and their differences between the study group were consistent with our previous findings (Blood et al., 2011; Johnson et al., 2018).

A limitation of this study is a significant loss to follow-up for the full duration of the study; however, for the first six months loss to follow-up was below 35%, one of 16 criteria used by Kennedy et al. to evaluate the quality of workplace interventions for upper extremity musculoskeletal disorders (Kennedy et al., 2010; Van Eerd et al., 2016). In addition, the loss-of-follow up was a result of several real-world aspects of completing workplace interventions. The trucking industry is well known for the high rate of driver turnover. Because the intervention required the coordination with a single company, when a driver left the company the intervention was unable to follow them. We did consider this for the baseline recruitment numbers as described in the methods.

We did compare the baseline data between those lost to follow-up and those who remained in the study to confirm no differences in the demographics, pain, and disability outcome measures between those two groups. Survey response rates among drivers still working were acceptable. We also assumed that the seat was always turned on; however, we were unable to verify this assumption with all drivers. We did explore several analyses other than the intent to treat, such as stratified analysis of those with the highest levels back pain – none of these exploratory analyses changed the findings.

A major strength of the study is its use of an experimental study design of a randomized controlled trial, where the exposure to WBV was significantly manipulated. Few studies relating occupational exposures to health outcomes have had such opportunities to change exposure, especially at the individual level, and to examine WBV. Such study designs can make stronger statements about causality of the exposure and a health outcome than observational studies. Because we saw similar changes in the pain outcomes in both arms of the study, the study is unable to support such causal claims in this instance.

This lack of causality may be due to the intervention approach serving as a secondary prevention effort – that is, the drivers had to have had LBP to be eligible to participate, and researchers were looking for a reduction in their LBP. The secondary prevention approach was done for feasibility purposes as it often requires fewer participants for statistical power and is the most common approach for workplace interventions for musculoskeletal disorders (Kennedy et al., 2010; Van Eerd et al., 2016). A better approach to test out causality would be to begin with a pain free cohort and look for new incidents of pain. Doing so, however, requires many more drivers to participate to account for incident rates rather than looking for reduction in pain and disability. The inclusion criteria of having back pain may have also contributed to high rates of turnover and loss of follow up (Lavender & Marras, 1994), limiting the study's overall efficacy.

Other strengths of the study include a longer follow-up period (two years), direct statistical comparison between the two arms, documented changes in exposure, and the use of intent-to-treat analysis.

In addition, while our randomization did appear effective in creating populations for the study's two arms that were not statistically different, there are other unmeasured factors that could have contributed to omitted variable bias in health outcome measurements, including psychosocial factors (NRC/IOM, 2001). Recruiting within a single company may help reduce the variability of these organizational factors; however, the multiple terminals across various geographical regions may increase the variability and differences across the two study arms for these unmeasured factors.

In conclusion, reducing WBV exposure through an active seat suspension system may be a promising approach to improve driver LBP and disability index. The results suggest other factors such as postures may also be influential in this regard. Therefore, reducing WBV exposure should be part of a comprehensive or integrated approach to improve overall driver musculoskeletal health.

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REFERENCES

(ISO), I. O. f. S. (1997). ISO 2631–1: Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part I: general requirements. In

(ISO), I. O. f. S. (2004). ISO 2631–5: Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part V: method for evaluation of vibration containing multiple shocks. In

Altman DG, & Bland JM (1999). How to randomise. Bmj, 319(7211), 703–704. doi:10.1136/bmj.319.7211.703 [PubMed: 10480833]

Amick BC 3rd, Habeck RV, Ossmann J, Fossel AH, Keller R, & Katz JN (2004). Predictors of successful work role functioning after carpal tunnel release surgery. J Occup Environ Med, 46(5), 490–500. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/15167398 [PubMed: 15167398]

Amick BC 3rd, Robertson MM, DeRango K, Bazzani L, Moore A, Rooney T, & Harrist R (2003). Effect of office ergonomics intervention on reducing musculoskeletal symptoms. Spine, 28(24), 2706–2711. Retrieved from http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=14673374 [PubMed: 14673374]

Bernard T (1997). Musculoskeletal disorders and workplace factors (DHHS Publication (NIOSH) 97–141). Retrieved from Washington, D.C.: http://www.cdc.gov/niosh/docs/97-141/pdfs/97-141.pdf

Blood RP, Dennerlein JT, Lewis C, Rynell P, & Johnson PW (2011). Evaluating whole-body vibration exposure engineering control options in a population of semi-truck drivers: Comparison of an active and passive suspension seat. Paper presented at the Human Factors and Ergonomics Society's 55th Annual Meeting, Las Vegas.

Blood RP, Yost MG, Camp JE, & Ching RP (2015). Whole-body Vibration Exposure Intervention among Professional Bus and Truck Drivers: A Laboratory Evaluation of Seat-suspension Designs. J Occup Environ Hyg, 12(6), 351–362. doi:10.1080/15459624.2014.989357 [PubMed: 25625530]

BLS, B. o. L. S. (2021). MSD by part of body affected by days away from work (Number, Rate, Median). Retrieved from Washington DC: https://www.bls.gov/iif/oshwc/osh/case/msd_cd_r2_00_2019.xlsx

Bovenzi M (2005). Health effects of mechanical vibration. G Ital Med Lav Ergon, 27(1), 58–64. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/15915675 [PubMed: 15915675]

Bovenzi M (2009). Metrics of whole-body vibration and exposure-response relationship for low back pain in professional drivers: a prospective cohort study. Int Arch Occup Environ Health, 82(7), 893–917. doi:10.1007/s00420-008-0376-3 [PubMed: 18953559]

Bovenzi M (2010). A longitudinal study of low back pain and daily vibration exposure in professional drivers. Ind Health, 48(5), 584–595. [PubMed: 20953075]

Bovenzi M, & Schust M (2021). A prospective cohort study of low-back outcomes and alternative measures of cumulative external and internal vibration load on the lumbar spine of professional drivers. Scand J Work Environ Health, 47(4), 277–286. doi:10.5271/sjweh.3947 [PubMed: 33522594]

Bovenzi M, Schust M, & Mauro M (2017). An overview of low back pain and occupational exposures to whole-body vibration and mechanical shocks. Med Lav, 108(6), 419–433. doi:10.23749/mdl.v108i6.6639 [PubMed: 29240039]

Burstrom L, Nilsson T, & Wahlstrom J (2015). Whole-body vibration and the risk of low back pain and sciatica: a systematic review and meta-analysis. Int Arch Occup Environ Health, 88(4), 403–418. doi:10.1007/s00420-014-0971-4 [PubMed: 25142739]

Davis K, Dunning K, Jewell G, & Lockey J (2014). Cost and disability trends of work-related musculoskeletal disorders in Ohio. Occup Med (Lond), 64(8), 608–615. doi:10.1093/occmed/kqu126 [PubMed: 25298392]

Dennerlein JT, Soumekh FS, Fossel AH, Amick BC 3rd, Keller RB, & Katz JN (2002). Longer distal motor latency predicts better outcomes of carpal tunnel release. J Occup Environ Med, 44(2), 176–183. [PubMed: 11851219]

Fairbank JC, Couper J, Davies JB, & O'Brien JP (1980). The Oswestry low back pain disability questionnaire. Physiotherapy, 66(8), 271–273. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/6450426 [PubMed: 6450426]

Fairbank JC, & Pynsent PB (2000). The Oswestry Disability Index. Spine (Phila Pa 1976), 25(22), 2940–2952; discussion 2952. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11074683 [PubMed: 11074683]

Jack RJ, & Eger T (2008). The effects of Posture on seat-to-head Whole-Body Vibration Transmission. Journal of Low Frequency Noise, Vibration and Active Control, 27(4), 309–325. doi:10.1260/026309208786926831

Johanning E (2011). Vibration and shock exposure of maintenance-of-way vehicles in the railroad industry. Appl Ergon, 42(4), 555–562. doi:10.1016/j.apergo.2010.06.018 [PubMed: 20870218]

Johnson PW, Zigman M, Ibbotson J, Dennerlein JT, & Kim JH (2018). A Randomized Controlled Trial of a Truck Seat Intervention: Part 1-Assessment of Whole Body Vibration Exposures. Ann Work Expo Health, 62(8), 990–999. doi:10.1093/annweh/wxy062 [PubMed: 30016417]

Katz JN, Keller RB, Fossel AH, Punnett L, Bessette L, Simmons BP, & Mooney N (1997). Predictors of return to work following carpal tunnel release. Am J Ind Med, 31(1), 85–91. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/8986259 [PubMed: 8986259]

Kennedy CA, Amick BC 3rd, Dennerlein JT, Brewer S, Catli S, Williams R, … Rempel D (2010). Systematic review of the role of occupational health and safety interventions in the prevention of upper extremity musculoskeletal symptoms, signs, disorders, injuries, claims and lost time. J Occup Rehabil, 20(2), 127–162. doi:10.1007/s10926-009-9211-2 [PubMed: 19885644]

Kim JH, Marin LS, & Dennerlein JT (2018). Evaluation of commercially available seat suspensions to reduce whole body vibration exposures in mining heavy equipment vehicle operators. Appl Ergon, 71, 78–86. doi:10.1016/j.apergo.2018.04.003 [PubMed: 29764617]

Kim JH, Zigman M, Aulck LS, Ibbotson JA, Dennerlein JT, & Johnson PW (2016). Whole Body Vibration Exposures and Health Status among Professional Truck Drivers: A Cross-sectional Analysis. Ann Occup Hyg, 60(8), 936–948. doi:10.1093/annhyg/mew040 [PubMed: 27385776]

Kim JH, Zigman M, Dennerlein JT, & Johnson PW (2018). A Randomized Controlled Trial of a Truck Seat Intervention: Part 2-Associations Between Whole-Body Vibration Exposures and Health Outcomes. Ann Work Expo Health, 62(8), 1000–1011. doi:10.1093/annweh/wxy063 [PubMed: 30016393]

Lauridsen HH, Hartvigsen J, Manniche C, Korsholm L, & Grunnet-Nilsson N (2006). Responsiveness and minimal clinically important difference for pain and disability instruments in low back pain patients. BMC Musculoskelet Disord, 7, 82. doi:10.1186/1471-2474-7-82 [PubMed: 17064410]

Lavender SA, & Marras WS (1994). The use of turnover rate as a passive surveillance indicator for potential low back disorders. Ergonomics, 37(6), 971–978. doi:10.1080/00140139408963710 [PubMed: 8026454]

Leigh JP (2011). Economic burden of occupational injury and illness in the United States. Milbank Q, 89(4), 728–772. doi:10.1111/j.1468-0009.2011.00648.x [PubMed: 22188353]

Lerner D, Amick BC 3rd, Rogers WH, Malspeis S, Bungay K, & Cynn D (2001). The Work Limitations Questionnaire. Med Care, 39(1), 72–85. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11176545 [PubMed: 11176545]

Marin LS, Rodriguez AC, Rey-Becerra E, Piedrahita H, Barrero LH, Dennerlein JT, & Johnson PW (2017). Assessment of Whole-Body Vibration Exposure in Mining Earth-moving Equipment and Other Vehicles Used in Surface Mining. Ann Work Expo Health, 61(6), 669–680. doi:10.1093/annweh/wxx043 [PubMed: 28637189]

McCarney R, Warner J, Iliffe S, van Haselen R, Griffin M, & Fisher P (2007). The Hawthorne Effect: a randomised, controlled trial. BMC Med Res Methodol, 7, 30. doi:10.1186/1471-2288-7-30 [PubMed: 17608932]

NRC/IOM, N. R. C. a. I. o. M. (2001). Musculoskeletal Disorders and the workplaces: Low Back and Upper Extremities. Washington, D.C: National Academy Press.

Pope MH, & Hansson TH (1992). Vibration of the spine and low back pain. Clin Orthop Relat Res(279), 49–59. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/1534724

Punnett L, Pruss-Utun A, Nelson DI, Fingerhut MA, Leigh J, Tak S, & Phillips S (2005). Estimating the global burden of low back pain attributable to combined occupational exposures. Am J Ind Med, 48(6), 459–469. doi:10.1002/ajim.20232 [PubMed: 16299708]

Raffler N, Rissler J, Ellegast R, Schikowsky C, Kraus T, & Ochsmann E (2017). Combined exposures of whole-body vibration and awkward posture: a cross sectional investigation among occupational drivers by means of simultaneous field measurements. Ergonomics, 60(11), 1564–1575. doi:10.1080/00140139.2017.1314554 [PubMed: 28402232]

Rahmatalla S, Xia T, Contratto M, Kopp G, Wilder D, Frey Law L, & Ankrum J (2008). Three-dimensional motion capture protocol for seated operator in whole body vibration. International Journal of Industrial Ergonomics, 38(5), 425–433. doi:10.1016/j.ergon.2007.08.015

Rauser E, Foley M, Bonauto D, Edwards S, Spielholz P, & Silverstein B (2008). Preventing Injuries in the Trucking Industry. Retrieved from http://www.lni.wa.gov/Safety/Research/Files/Trucking/PreventingTruckingInjuries.pdf

Rauser E, Smith C, & Williams J (2014). Trucking Industry: Examining Injuries for Prevension, 2006–2012. Retrieved from http://www.lni.wa.gov/Safety/Research/Files/Trucking/901482014.pdf

Robertson MM, Ciriello VM, & Garabet AM (2013). Office ergonomics training and a sit-stand workstation: effects on musculoskeletal and visual symptoms and performance of office workers. Appl Ergon, 44(1), 73–85. doi:10.1016/j.apergo.2012.05.001 [PubMed: 22727324]

Silverstein B (2010, 21 July 2010). [Back Pain in Truckers].

Smith CK, & Williams J (2014). Work related injuries in Washington State's Trucking Industry, by industry sector and occupation. Accid Anal Prev, 65, 63–71. doi:10.1016/j.aap.2013.12.012 [PubMed: 24440505]

Snook SH (2004). Work-related low back pain: secondary intervention. J Electromyogr Kinesiol, 14(1), 153–160. Retrieved from http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=14759760 [PubMed: 14759760]

Teschke K (1999). Whole body vibration and back disorders among motor vehicle drivers and heavy equipment operators: A review of the scientific evidence. Retrieved from Vancouver, B.C.: http://www.cher.ubc.ca/PDFs/WBV_Report.pdf

Thamsuwan O, Blood RP, Ching RP, Boyle L, & Johnson PW (2013). Whole body vibration exposures in bus drivers: A comparison between a high-floor coach and a low-floor city bus. International Journal of Industrial Ergonomics, 43(1), 9–17. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S0169814112000947

Van Eerd D, Munhall C, Irvin E, Rempel D, Brewer S, van der Beek AJ, … Amick B (2016). Effectiveness of workplace interventions in the prevention of upper extremity musculoskeletal disorders and symptoms: an update of the evidence. Occup Environ Med, 73(1), 62–70. doi:10.1136/oemed-2015-102992 [PubMed: 26552695]

Vianin M (2008). Psychometric properties and clinical usefulness of the Oswestry Disability Index. J Chiropr Med, 7(4), 161–163. doi:10.1016/j.jcm.2008.07.001 [PubMed: 19646379]

Ware J Jr., Kosinski M, & Keller SD (1996). A 12-Item Short-Form Health Survey: construction of scales and preliminary tests of reliability and validity. Med Care, 34(3), 220–233. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/8628042 [PubMed: 8628042]

Webster BS, & Snook SH (1994). The cost of 1989 workers' compensation low back pain claims. Spine (Phila Pa 1976), 19(10), 1111–1115; discussion 1116. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/8059265 [PubMed: 8059265]

Zimmermann CL, & Cook TM (1997). Effects of vibration frequency and postural changes on human responses to seated whole-body vibration exposure. Int Arch Occup Environ Health, 69(3), 165–179. doi:10.1007/s004200050133 [PubMed: 9049667]

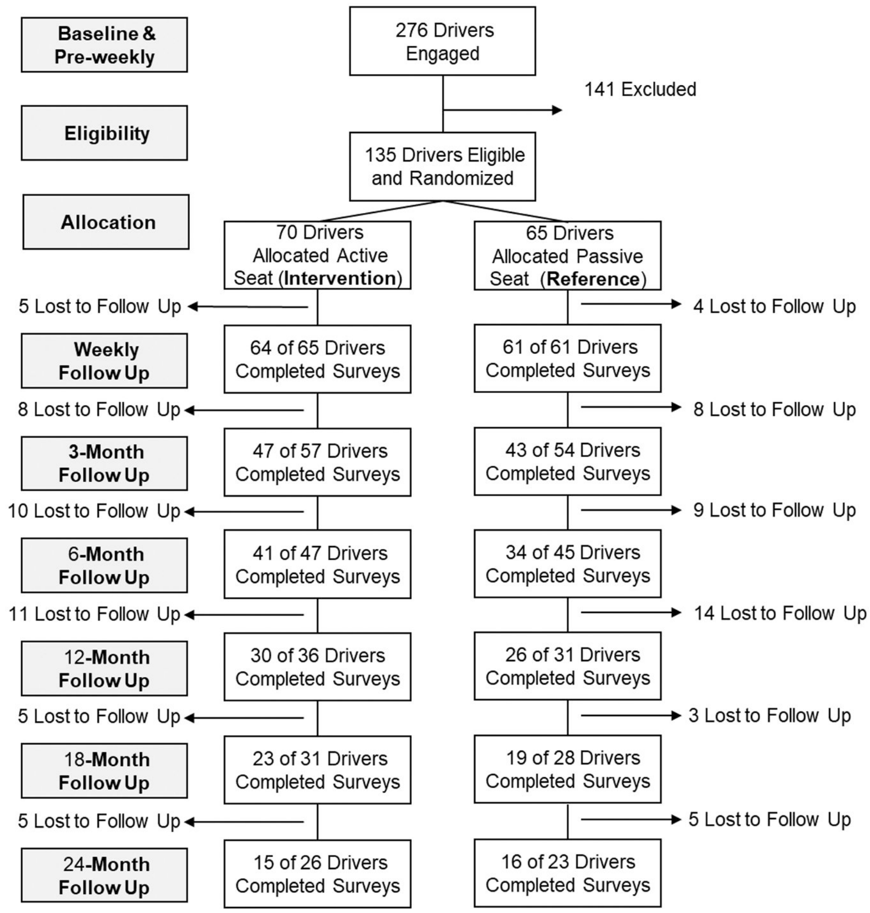

Figure 1:
Study Consort Diagram.

Table 1:

Demographics at allocation from baseline survey

	Active Seat (n=70) Intervention	Passive Seat (n=65) Reference	Baseline Comparison
	Mean (SD)	**Mean (SD)**	***p-value***
Age (Years)	48 (10)	48 (11)	0.88
Tenure (Years)	12 (10)	12 (11)	0.74
Body Mass Index (BMI)	35 (7)	33 (7)	0.19
SF 12 General **			
Physical Health	46 (9)	47 (9)	0.52
Mental health	52 (8)	51 (9)	0.39
	N. (%)	N. (%)	
Gender			
Male	63 (90%)	59 (91%)	0.88
Female	7 (10%)	6 (9%)	
Race			0.47
White	52 (75%)	51 (80%)	
Black	6 (9%)	7 (11%)	
Hispanic	8 (12%)	4 (6%)	
Other	3 (4%)	2 (3%)	
Hispanic/ Non-Hispanic			0.62
Hispanic	7 (11%)	4 (6%)	
Non-Hispanic	60 (87%)	59 (92%)	
Education			0.78
High School or Less	25 (36%)	21 (34%)	
Some College or more	44 (64%)	41 (66%)	
Intervention Targets & Outcomes	Mean (SD)	Mean (SD)	
Low Back Pain Severity (Range: 0–10)	3.8 (2.8)	3.8 (2.6)	0.94
Sum of Body Part Pain (Range: 0–70)	17 (13)	16 (12)	0.75
Oswestry Disability (Range: 0–100)	11 (10)	10 (9)	0.54

*Demographic variables were compared across seat groups using a t-test for continuous and chi-square for categorical variables

**SF 12 Physical and Mental Health values have been normalized to the general US population with a mean value of 50 and standard deviation of 10.

Table 2:

Whole body vibration exposure metrics for the vertical axis

A(8)*** m/s^2	Active Seat* Intervention		Passive Seat** Reference		Comparison at time
	Mean (SD)	**N**	**Mean (SD)**	**N**	***p-value***
Baseline Values					
Pre-Intervention	0.36 (0.15)	20	0.36 (0.11)	31	0.88
Follow up					
Post-Interventions	**0.23 (0.08)**	24	0.31 (0.07)	26	<0.01
12-month	**0.19 (0.04)**	19	0.36 (0.12)	16	<0.01
24-month	**0.16 (0.02)**	4	0.31 (0.06)	5	<0.01
VDV(8)* $m/s^{1.75}$**	**Active Seat* Intervention**		**Passive Seat** Reference**		**Comparison at time**
	Mean (SD)	**N**	**Mean (SD)**	**N**	***p-value***
Baseline Values					
Pre-Intervention	8.9 (2.7)	20	9.0 (2.3)	31	0.92
Follow up					
Post-Interventions	**7.1 (2.1)**	24	8.0 (1.7)	26	0.10
12-month	**5.6 (1.6)**	19	9.0 (2.4)	16	<0.01
24-month	**4.6 (0.7)**	4	8.9 (2.5)	5	0.01

*One-way ANOVA results: dof = 3, f_{ratio} = 13.1, time: $p < 0.01$

**One-way ANOVA results: dof = 3, f_{ratio} = 1.25, time: $p = 0.30$

***Two-way ANOVA results: dof = 7, f_{ratio} = 13.1, time: $p < 0.01$, seat: $p < 0.01$, time*seat: $p <0.01$,

*One-way ANOVA results: dof = 3, f_{ratio} = 10.2, time: $p < 0.01$,

**One-way ANOVA results: dof = 3, f_{ratio} = 1.25, time: $p = 0.30$,

***Two-way ANOVA results: dof = 7, f_{ratio} = 7.70, time: $p < 0.01$, seat: $p < 0.01$, time*seat: $p <0.01$

Bolded values indicated significant difference between follow up and baseline based on Dunnett Least Square Means Test within each seat.

Action limits for A(8) is $0.5 m/s^2$ and for VDV(9) is $9.1\ m/s^{1.75}$.

Table 3:

Low back pain severity at baseline and change over time

LBP Severity (0–10)	Active Seat Intervention		Passive Seat Reference		Comparison at time
	Mean (SD)	**N**	**Mean (SD)**	**N**	***p-value***
Baseline Values					
Baseline Survey	3.8 (2.8)	70	3.8 (2.6)	65	0.94
Pre-weekly four-week average	3.8 (2.2)	70	3.9 (2.2)	65	0.58
Difference at Follow up	Mean (95% CI)		Mean (95% CI)	N	
Post-Weekly four-week average	**−1.5 [−2.0, −1.0]**	64	**−1.6 [−2.1, −1.2]**	61	0.69
3-Month	**−1.4 [−2.1, −0.7]**	46	**−1.5 [−2.3, −0.8]**	41	0.76
6-Month	**−1.9 [−2.8, −1.0]**	41	**−2.2 [−2.9, −1.5]**	33	0.58
12-month	**−1.7 [−2.9, −0.4]**	29	**−2.2 [−3.3, −1.2]**	26	0.47
18-month	**−1.8 [−3.0, −0.7]**	23	**−2.2 [−3.6, −0.8]**	18	0.64
24-month	−0.73 [−2.6, 1.1]	11	**−2.0 [−3.5, −0.5]**	12	0.25

Bolded values indicated the 95 percent confidence interval of the mean difference between follow up and baseline did not include 0 and are hence statistically significant different than baseline.

Post weekly four-week average was relative to the pre-weekly four-week average

Table 4:

Sum of pain in all seven body regions at baseline and change over time

Sum of Body Pain (0–70 scale)	Active Seat Intervention		Passive Seat Reference		Comparison at time
	Mean (SD)	**N**	**Mean (SD)**	**N**	***p-value***
Baseline Values					
Baseline Survey	17 (13)	70	16 (12)	65	0.75
Pre-weekly four-week average	16 (12)	70	17 (12)	65	0.54
Difference at Follow up	Mean (95% CI)		Mean (95% CI)		
Post-Weekly four-week average	**−7 [−10, −4]**	63	**−7 [−9, −5]**	60	0.92
3-Month	**−8 [−12, −5]**	44	**−6 [−9, −3]**	40	0.46
6-Month	**−10 [−15, −6]**	39	**−9 [−12, −6]**	33	0.57
12-month	**−11 [−16, −5]**	27	**−9 [−15, −4]**	25	0.75
18-month	**−11 [−18, −5]**	22	**−11 [−17, −5]**	18	0.85
24-month	−4 [−16, 8]	10	−5 [−12, 2]	12	0.88

Bolded values indicated the 95 percent confidence interval of the mean difference between follow up and baseline did not include 0 and are hence statistically significant different than baseline.

Post weekly four-week average was relative to the pre-weekly four-week average.

Table 5:

Low back pain disability at baseline and change over time

Oswestry Index (0–100)	**Active Seat Intervention**		**Passive Seat Reference**		**Comparison at time**
	Mean (SD)	**N**	**Mean (SD)**	**N**	***p-value***
Baseline Values					
Baseline Survey	11 (10)	70	10 (9)	65	0.54
Difference at Follow up	Mean (95% CI)		Mean (95% CI)		
3-Month	**−2.8 [−5.3, −0.3]**	44	−0.1 [−2.1, 1.9]	40	0.09
6-Month	−2.7 [−6.1, 0.8]	40	**−3.6 [−5.6, −1.5]**	34	0.65
12-month	**−6.1 [−9.4, −2.8]**	28	−2.3 [−5.7, 1.0]	26	0.10
18-month	**−4.6 [−6.8, −2.3]**	22	−0.9 [−4.5, 2.7]	18	0.07
24-month	1.2 [−7.1, 10.8]	15	0.0 [−5.1 5.0]	15	0.81

Bolded values indicated the 95 percent confidence interval of the mean difference between follow up and baseline did not include 0 and are hence statistically significant different than baseline.