Journal of Athletic Training 2016;51(11):981–990
doi: 10.4085/1062-6050-51.9.13

www.natajournals.org

Vehicle Exposure and Spinal Musculature Fatigue in Military Warfighters: A Meta-Analysis

Roger O. Kollock, PhD, ATC, CSCS*; Kenneth E. Games, PhD, LAT, ATC†; Alan E. Wilson, PhD‡; JoEllen M. Sefton, PhD, ATC§

*Department of Kinesiology and Rehabilitative Sciences, The University of Tulsa, OK; †Department of Applied Medicine and Rehabilitation, Indiana State University, Terre Haute; ‡School of Fisheries, Aquaculture, and Aquatic Sciences, Auburn University, AL; §Warrior Research Center, School of Kinesiology, Auburn University, AL

Context: Spinal musculature fatigue from vehicle exposure may place warfighters at risk for spinal injuries and pain. Research on the relationship between vehicle exposure and spinal musculature fatigue is conflicting. A better understanding of the effect of military duty on musculoskeletal function is needed before sports medicine teams can develop injury-prevention programs.

Objective: To determine if the literature supports a definite effect of vehicle exposure on spinal musculature fatigue.

Data Sources: We searched the MEDLINE, Military & Government Collection (EBSCO), National Institute for Occupational Safety and Health Technical Information Center, PubMed, and Web of Science databases for articles published between January 1990 and September 2015.

Study Selection: To be included, a study required a clear sampling method, preexposure and postexposure assessments of fatigue, a defined objective measurement of fatigue, a defined exposure time, and a study goal of exposing participants to forces related to vehicle exposure.

Data Extraction: Sample size, mean preexposure and postexposure measures of fatigue, vehicle type, and exposure time.

Data Synthesis: Six studies met the inclusion criteria. We used the Scottish Intercollegiate Guidelines Network algorithm to determine the appropriate tool for quality appraisal of each article. Unweighted random-effects model meta-analyses were conducted, and a natural log response ratio was used as the effect metric. The overall meta-analysis demonstrated that vehicle exposure increased fatigue of the spinal musculature ($P = .03$; natural log response ratio = –0.22, 95% confidence interval = –0.42, –0.02). Using the spinal region as a moderator, we observed that vehicle ride exposure significantly increased fatigue at the lumbar musculature ($P = .02$; natural log response ratio = –0.27, 95% confidence interval = –0.50, –0.04) but not at the cervical or thoracic region.

Conclusions: Vehicle exposure increased fatigue at the lumbar region.

Key Words: soldiers, vibration, mechanical shock, *g* forces, acceleration

Musculoskeletal injuries have become one of the top problems for our military. The rigorous physical demands of training and combat situations experienced by warfighters have been the driving force behind the move toward a sports medicine model of care: encouraging service members to think and train as athletes and including athletic trainers in the care and prevention of military injuries.[1] Research into specific military-related mechanisms of injury is required if we are to properly serve our military warfighters.

A common injury risk factor may be daily exposure to military vehicles. Service members are regularly exposed to military vehicles on repeated days and for long durations. In using these highly specialized vehicles designed for land, water, and air, military warfighters are often exposed to bouts of whole-body vibration, mechanical shock, and acceleration (+Gz forces) as a duty requirement. Service members with almost daily exposure to military vehicles (eg, M1 Abrams tank, Bradley Fighting Vehicle, Stryker, and rotatory and fixed-wing aircraft) are frequently termed *mounted warfighters*. The constant loading of the spinal column or prolonged sitting in military vehicles (or both) may contribute to the development of spinal injuries and pain.[2] Mounted warfighters and other individuals in vehicle-dependent occupations (eg, heavy equipment operators, professional drivers, commercial pilots) often experience pain from spinal musculoskeletal conditions. This pain can be debilitating, compromise mission efficacy and completion, limit warfighter duty and ability to deploy, be career ending, and affect overall military readiness.[3,4] If exposure to vehicles is a contributing factor to injury, the development of injury-prevention programs may enable military warfighters to avoid long-term pain and disability. Clearly, a greater understanding of how vehicle exposure may affect a warfighter's body is required.

Spinal injuries and pain are common complaints in mounted warfighters.[4–8] In a 2012 study,[6] investigators observed that 64% to 89% of military helicopter or fighter-jet pilots reported some degree of neck and back pain. A sample of fixed-wing and rotary-wing pilots revealed cervical disc degeneration in 55% and lumbar spinal degeneration in 60%[7]; another group[8] found that 50% of jet pilots in the Royal Norwegian Air Force had neck pain and 23% had back pain in the previous 12 months. These conditions affect the health and wellness of service members.

Table 1. Database Search Strategy: Search Terms by Category

Results for *Vehicle Type*		Results for *Forces*		Results for *Fatigue*		Results for *Spine*
Military vehicle		Vibration		Muscle fatigue		Spine
OR		OR		OR		OR
Military aircraft		+Gz forces		Neuromuscular fatigue		Neck
OR		OR		OR		OR
Simulator	AND	Shock	AND	Muscle endurance	AND	Lumbar
OR		OR		OR		OR
Vehicle		Exposure		Muscle activity		Cervical
OR		OR		OR		OR
Aircraft		Repeated loading		EMG		Thoracic
OR		OR		OR		*
Military		Loading		Spine musculature		*
*		OR		OR		*
*		Impact		Muscle function		*

One potential injury risk factor hypothesized by researchers[9,10] is spinal musculature fatigue, which may be a side effect of ride (or flight)-related forces or prolonged static postures (or both).[9,10] Muscle activity plays a key role in postural control and injury protection and contributes to the ability of the spinal column to endure prolonged standing or seated vehicle exposure.[11] The muscles acting on the spine (eg, erector spinae, multifidus)[9,12] may become fatigued under constant or repeated exposure to vibration, mechanical shock, or +Gz forces. These forces likely affect muscle recruitment and reflex responses, thereby influencing neuromuscular control and leading to postural alterations during prolonged vehicle exposure. For example, fatigue of the lumbar musculature related to vehicle exposure could alter seating posture, forcing the lumbar region into more kyphosis and altering the normal curvature in the proximal portion of the spine. In an attempt to maintain a forward gaze, the mounted warfighter may compensate by further extending the neck. This combination of events likely puts the mounted warfighter in a position of increased susceptibility to spinal injury and pain.[13,14]

Muscle fatigue caused by vehicle-exposure forces may reduce the ability of the spinal muscles to protect a warfighter's spinal column from the same types of ride-related forces that cause fatigue. Thus, vehicle-related spinal musculature fatigue presents potential detrimental effects for both mission performance and warfighter health.[4]

To explore the influence of vehicle exposure on muscle fatigue, investigators have used both vehicles and vehicle simulators (mostly the latter). Simulators designed to mimic the vibration, mechanical shock, or +Gz force patterns sustained by the operators and crew of a particular vehicle provide an opportunity to explore this relationship in a laboratory setting. Previous studies[9,15,16] of the effects of vehicle exposure on spinal musculature fatigue have produced conflicting results.

These contradictory reports highlight the need to summarize the available research in order to advance our understanding of the effect (if any) vehicle exposure has on spinal musculature fatigue. Although some reports point to fatigue as a potential injury risk factor for spinal injury or pain (or both),[9,16] another study[17] did not show fatigue-related changes in muscle activity at the spine. Therefore, the purpose of our study was to determine if the literature supports an effect of vehicle exposure on spinal musculature fatigue. Insight into the influence of vehicle exposure on spinal musculature fatigue is needed to help future investigators identify injury risk factors associated with the development of spinal conditions and pain in mounted warfighters. This information could then be used to develop injury-prevention programs and vehicle-use protocols and to help develop the next generation of military vehicles.

METHODS

Identification, Study Selection, and Data Extraction

An online search was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA[18]) protocol and using the MEDLINE, Military & Government Collection (EBSCO), National Institute for Occupational Safety and Health Technical Information Center, PubMed, and Web of Science databases. The search was designed to identify all articles published between January 1990 and September 2015 investigating the effects of vehicle exposure on spinal musculature fatigue. We searched the databases using combinations of the following terms and phrases: *aircraft*, *cervical*, *EMG*, *exposure*, *+Gz forces*, *impact*, *loading*, *lumbar*, *military*, *military aircraft*, *military vehicle*, *vehicle*, *muscle activity*, *muscle endurance*, *muscle fatigue*, *muscle function*, *neck*, *neuromuscular fatigue*, *repeated loading*, *shock*, *simulator*, *spine*, *spine musculature*, *thoracic*, and *vibration* (Table 1). In addition, we searched the reference lists of the acquired articles to find additional pertinent articles. Non-English publications were translated for inclusion, and attempts were made to contact researchers for unpublished data.

To reduce any possible selection bias, the inclusion criteria were set before the database search. For inclusion, all studies were required to have a clear sampling method, preexposure and postexposure assessments of fatigue, a defined objective metric of fatigue, a defined exposure time, and a goal of exposing participants to forces (eg, vibration, mechanical shock, and +Gz forces) related to vehicle exposure (Table 2). After screening the titles and abstracts, 2 authors (R.O.K., K.E.G.) assessed the relevant full-text articles. The authors resolved disagreements regarding publication eligibility either by consensus or by arbitration of a third author (J.M.S.) if disagreement continued. The authors extracted all relevant information from each eligible article: sample size, mean preexposure and

Table 2. Inclusion Criteria and Number of Data Points Each Study Contributed to the Overall Meta-Analysis

Study	Sample	Preexposure to Postexposure Assessment of Fatigue?	Objective Metric(s) of Fatigue	Exposure Time	Goal to Expose Participants to Ride-Related Forces?	Data Points Contributed, No.
Astrom et al[15]	20 Male, 17 female healthy volunteers with no history of musculoskeletal disorder	Pre-post	EMG MNF, RMS	3 min	Yes	8
Balasubramanian et al[9,a]	8 Male Indian Coast Guard helicopter pilots with no lower extremity injury, physical disability, or discomfort	Pre-post	EMG mean amplitude, MF, RMS	Average sortie duration = 2.06 ± 0.29 h	Yes	12
Hansson et al[20]	6 Men free of current back pain	Pre-post	EMG MNF, RMS	5 min	Yes	18
Santos et al[12]	12 Healthy men with no systematic or degenerative, neurologic, or musculoskeletal condition or low back pain requiring medical treatment within the previous 12 mo	Pre-post, recovery at 80 min, 100 min, 120 min	EMG average instantaneous mean power frequency	60 min	Yes	6
Li et al[16]	36 University staff members with no history of low back disease or injury or spinal deformity	18 Sections (1 initial and 17 post measures) each = 5 min	EMG MF	90 min	Yes	51
Cameron et al[19]	10 (Exposure = 420 min) and 8 (exposure = 240 min) healthy male US Army personnel	Pre-post	EMG MNF	7 h and 4 h	No	16

Abbreviations: EMG, electromyography; MF, median frequency; MNF, mean frequency; RMS, root mean square.

[a] We used 12 data points from Balasubramanian et al[9] for the first overall analysis but none for the second overall analysis.

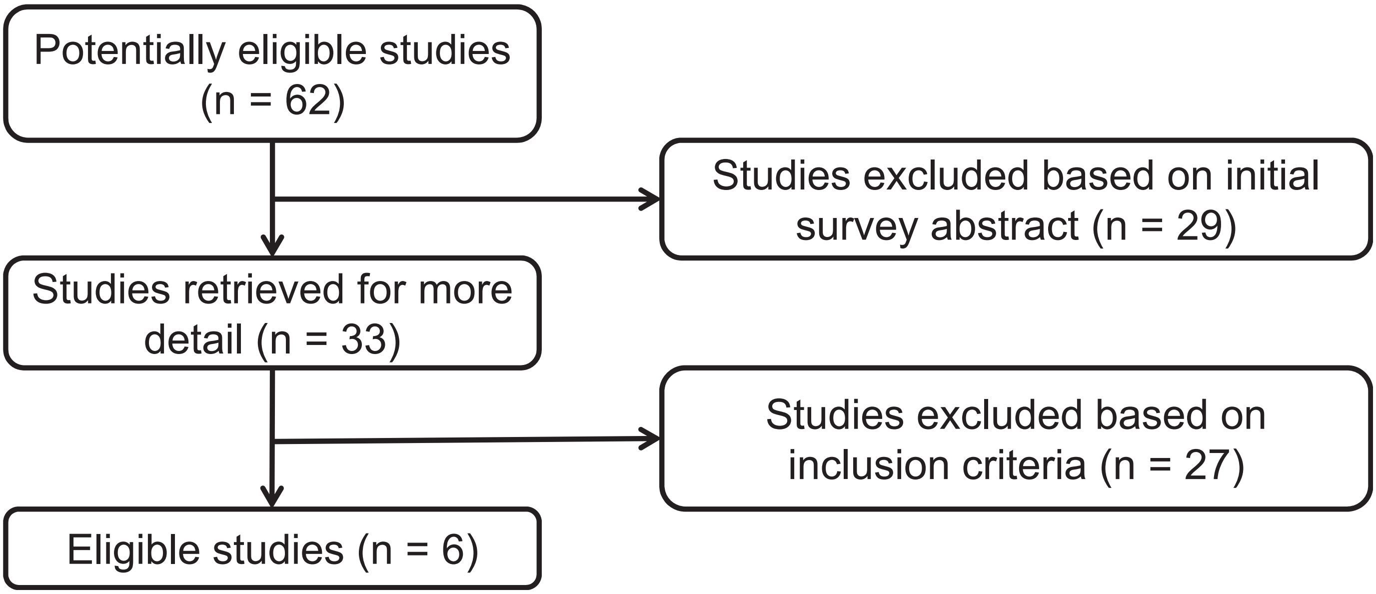

Figure 1. Outline of literature search and selection.

postexposure measures of fatigue, vehicle type (eg, simulator, rotary aircraft, or ground-based vehicle), and exposure time in hours. We used ImageJ (version 1.6.0; National Institutes of Health, Bethesda, MD) to extract the pertinent data contained in figures.

Data Analysis

All data extracted from published studies were entered into a custom spreadsheet (Excel version 2010; Microsoft Corp, Redmond, WA). Effect sizes were calculated as natural log-transformed response ratios (calculated as ln[preexposure/postexposure]) to account for the differences in fatigue outcome measures due to different electromyography (EMG) techniques (eg, mean frequency, root mean square). One advantage of this metric over others is that effect sizes are normally distributed around zero. When using this metric, an effect size with a 95% confidence interval (CI) that crosses zero indicates no statistical difference between preexposure and postexposure assessments of fatigue.[21] An effect size with a 95% CI that was less than zero indicated that vehicle exposure increased fatigue of the spinal musculature ($P < .05$). To simplify the interpretation of natural log-transformed effect sizes, absolute (nontransformed) postfatigue measurements that were 2.7 times or 7.4 times higher than paired absolute prefatigue measurements were equivalent to a –1.0 or –2.0 natural log-transformed response ratio effect size, respectively. Because error terms were not available for most studies, we analyzed effect sizes with an unweighted random-effects model using Comprehensive Meta-Analysis software (version 2.2.064; Biostatistics Programming Associates, Englewood, NJ). Spinal region (cervical, thoracic, and lumbar) and vehicle type (simulator, ground-based vehicle, fixed-wing aircraft, and rotary-wing aircraft) were moderators for separate subanalyses. In our study, a *simulator* represented any configuration used to mimic vehicle-exposure forces (eg, vibration, shock). The calculated summary effect for each analysis (overall and moderated analyses) represented the mean effect size of the analysis. Two separate random-effects meta-regressions were used to determine if there was a dose-response relationship between vehicle-exposure forces and fatigue of the thoracic and lumbar regions. Due to limited data, we could not perform a meta-regression for the cervical region. A funnel plot and fail-safe number analyses were used to determine if publication bias influenced our findings.

RESULTS

The search yielded 62 potentially relevant articles, and 6 studies met the inclusion criteria (Figure 1).[9,12,15,16,19,20] The characteristics of each study are described in Table 3. According to the Scottish Intercollegiate Guidelines Network algorithm for classifying study design, an appropriate checklist to assess study quality was not available as the included articles were observational studies with only a single study group. Thus, a quality of evidence score of 3 was assigned to all included studies. The funnel plot of the effect-size data was asymmetric, indicating a possible publication bias (Figure 2). In addition, the fail-safe N analysis determined that for the 2 *P* values below .05 (ie, ground-based simulators and all types of simulators), 63 and 76 negative effect sizes, respectively, would be required to increase the meta-analysis *P* value to more than .05. The significant fail-safe Ns calculated for the main meta-analysis and moderated analyses ranged between 63 and 91, with an average fail-safe N of 77 negative effect sizes required to increase the meta-analysis *P* value to more than .05. We calculated the fail-safe N according to the Rosenthal method.[22] This method determines the number of studies with nonsignificant results that would need to be added to increase the meta-analysis *P* value to more than the α level.[23] The calculation is based on the Stouffer method.[24]

Data Synthesis

The overall meta-analysis of 6 studies revealed that vehicle exposure increased fatigue of the spinal muscula-

Table 3. Study Characteristics

Study	Sample	Physical Characteristics, Mean ± SD			Assessment	Level of Evidence	Muscles Assessed by Region		
		Age, y	Height, cm	Weight, kg			Cervical	Thoracic	Lumbar
Astrom et al[15]	20 Healthy men 17 Healthy women	25.8 ± 4.1 25.9 ± 4.4	183.9 ± 5.7 167 ± 5.2	79.7 ± 9.7 61.2 ± 6.4	EMG MNF, RMS	3	Upper trapezius	No	No
Balasubramanian et al[9]	8 Male Indian Coast Guard helicopter pilots	36.55 ± 3.53	NA	NA	EMG MF, mean amplitude, RMS	3	Trapezius (lateral to C-7 midpoint and acromion)	No	Erector spinae (slightly above iliac crest)
Hansson et al[20]	6 Men	Range, 20–25	Range, 174–194	Range, 61–86	EMG MNF, RMS	3	Erector spinae (T-7 level, 3 cm lateral to spinous processes)	No	Erector spinae (L-3 level, 3 cm lateral to spinous processes)
Santos et al[12]	12 Healthy men	22 ± 2	180 ± 10	77 ± 9	EMG average instantaneous mean power frequency	3	Longissimus at L-1 level, iliocostalis lumborum at L-3 level, and multifidus at L-5 level	No	No
Li et al[16]	36 University staffers	23.9 ± 2.4	172.6 ± 3.5	66.6 ± 7.4	EMG MF	3	No	No	Erector spinae (L-3 level, 3 cm lateral to spinous processes)
Cameron et al[19]	10 (Exposure = 420 min) and 8 (exposure = 240 min) healthy male US Army personnel	NA	NA	NA	EMG MNF	3	No	Erector spinae, spinalis thoracic, longissimus thoracic, trapezius and latissimus dorsi (T-9 level)	Erector spinae (L-3 level)

Abbreviations: EMG, electromyography; MF, median frequency; MNF, mean frequency; NA, not available; RMS, root mean square.

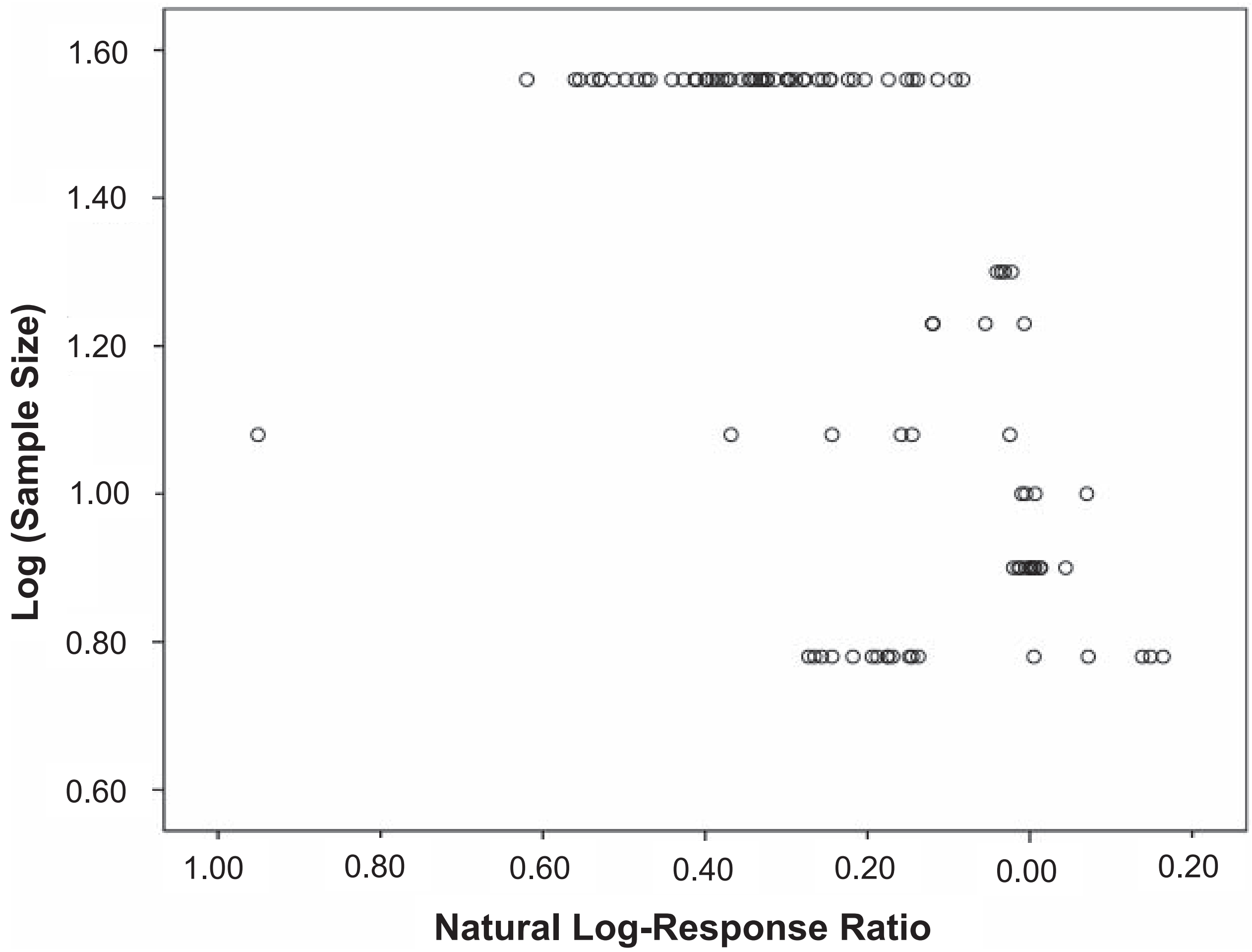

Figure 2. Funnel plot. Note: The results of Balasubramanian et al[9] were not included in the analyses.

ture ($P = .02$; natural log response ratio = –0.22, 95% CI = –0.41, –0.03). Vehicle exposure produced an effect on the lumbar spinal musculature at the lumbar region when spinal region (cervical, thoracic, lumbar) was used as a moderator ($P = .02$; natural log response ratio = –0.27, 95% CI = –0.48, –0.02). Vehicle exposure did not affect fatigue of the cervical ($P = .65$; natural log response ratio = –0.12, 95% CI = –0.64, 0.40) or thoracic ($P = .74$; natural log response ratio = –0.08, 95% CI = –0.55, 0.39) musculature. Vehicle exposure from ground-based vehicle simulators demonstrated an effect on fatigue of the spinal musculature when vehicle type was used as a moderator ($P = .03$; natural log response ratio = –0.24, 95% CI = –0.46, –0.03). Collectively, simulated vehicle exposure affected fatigue of the spinal musculature ($P = .03$; natural log response ratio = –0.22, 95% CI = –0.42, –0.02). Due to the lack of data collection for specific vehicles, we were unable to perform separate analyses using vehicle type (eg, Stryker) as a moderator.

Of the 6 studies included in this meta-analysis, 5 were conducted in a simulator. We removed the only vehicle-based study (Balasubramanian et al[9]) and recalculated the analysis to determine if this difference influenced our results. The forest plot for the overall and moderated analyses is shown in Figure 3. The results of the simulator-only overall and moderated analyses were similar to the results of the analysis of all 6 studies. For the overall meta-analysis (5 simulator studies; Table 4, Figure 3), we observed that vehicle exposure increased fatigue of the spinal musculature ($P = .03$; natural log response ratio = –0.22, 95% CI = –0.42, –0.02). We also found that vehicle ride exposure increased fatigue of the lumbar musculature only ($P = .02$; natural log response ratio = –0.27, 95% CI = –0 .50, –0.04) when spinal region was used as a moderator. Thoracic muscle fatigue was not increased by vehicle exposure ($P = .74$; natural log response ratio = –0.08, 95% CI = –0.55, 0.40). (A moderated analysis for the cervical region was not possible because removal of the Balasubramanian et al[9] data resulted in only 1 remaining article on the cervical region.) Vehicle exposure from ground-based vehicle simulators also demonstrated an effect on fatigue of the spinal musculature ($P = .03$; natural log response ratio = –0.24, 95% CI = –0.46, –0.03).

DISCUSSION

Our study revealed that vehicle exposure increased fatigue of the lumbar musculature, which suggests that spinal injury-prevention programs should focus on fatigue of this region. Although many factors could be involved in these findings, the results reinforce the anecdotal evidence that vehicle exposure may contribute to spinal injury and pain and support the need for additional research in this area to better protect our warfighters.

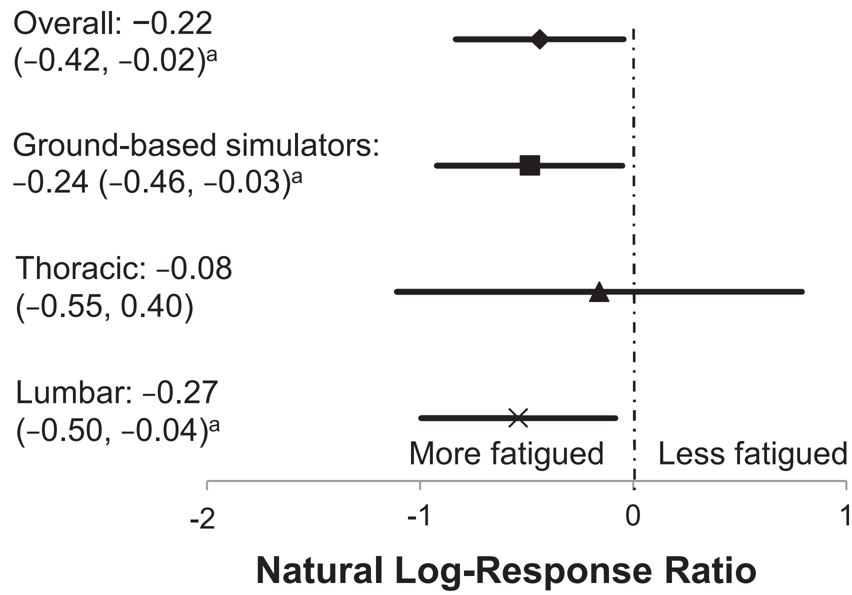

Figure 3. Forest plot of overall and moderated analysis: natural log-response ratio (95% confidence interval). [a] ***P*** **$\leq$ .05.**

Authors of the included studies commonly used EMG measures of mean frequency, median frequency, or root mean square to assess fatigue. The methods were often similar, but 2 groups[12,25] who measured fatigue using similar EMG signal-processing methods in the same spinal regions reported contradictory findings. Moreover, we observed that authors[9,15,20] who used multiple EMG techniques often reported a significant increase in fatigue with 1 signal-processing technique but not another. For example, 1 group of researchers[20] noted that mean frequency decreased at a vibration frequency of 5 Hz, indicating lumbar fatigue in the erector spinae but conversely demonstrated a nonsignificant decrease in root mean square values in the same muscles. Typically, a decrease in mean (or median) frequency and an increase in root mean square EMG signal indicate muscle fatigue.[15,26,27] The authors[20] hypothesized that the reason for this contradictory outcome was the high-level vibratory environment of the experimental condition, suggesting that it decreased the rate of metabolite removal, which influenced the root mean square measure. Others[15,28,29] have reported that root mean square is a more uncertain measure of fatigue because its values can be influenced by actively developed force in a muscle. However, each of the aforementioned EMG processing methods presents limitations. Given that force and fatigue both influence EMG spectrum and amplitude, it may be necessary for future researchers to use a processing technique that can provide information on whether EMG changes are fatigue induced or force related, such as joint analysis of EMG spectrum and amplitude.[29,30] None of the studies included in our analysis used this technique.

Statistical synthesis of the data allowed us to evaluate the effect of vehicle exposure on fatigue of the thoracic and lumbar muscular regions across multiple studies. Analyses using spinal region as a modifier revealed that vehicle exposure increased fatigue in the lumbar musculature but had no effect on the thoracic musculature. The finding of fatigue in the lumbar region is not surprising considering the high prevalence of low back pain in pilots.[4,6–8] This suggests a possible link between lumbar muscle fatigue and low back pain. Investigators in 1 study[9] reported a strong correlation ($r^2 = 0.86$) between total flying hours and low back pain in helicopter pilots. Arguably, fatigue of the lumbar musculature could result in an altered sitting posture, such that the lumbar spine adopts a more kyphotic curvature, which increases stress on the lumbar region, thereby elevating the risk of developing a spinal injury or pain. It should be noted that studies of the lumbar spine accounted for 74 of the data points included in the analysis (approximately 75%), which may have influenced these results. Additionally, most of this research was completed in ground-based vehicle simulators. Clearly, more work is needed to assess any connection between actual vehicle exposure and the development of lumbar injury and pain.

We removed 1 study[9] from the analyses to allow for a clearer interpretation of the data. This study was the only one to use an aircraft (ie, not a simulator) that met the inclusion criteria. The outcomes remained the same for the lumbar and thoracic analyses, suggesting that simulators may produce results in these body regions that are similar

Table 4. Summary Effects of Overall and Moderated Analyses Including Number of Data Points Used in the Analysis[a]

Analysis	Natural Log-Response Ratio	95% Confidence Interval	*P* Value	Data Points, No.
Overall	−0.22	−0.42, −0.02	.03	99
Ground-based simulators	−0.24	−0.46, −0.03	.03	65
Thoracic	−0.08	−0.55, 0.40	.74	17
Lumbar	−0.27	−0.50, −0.04	.02	74

[a] The data of Balasubramanian et al[9] were not included in the analyses.

to studies in actual vehicles. The deleted study represented 1 of only 2 investigations to evaluate cervical fatigue that met the inclusion criteria. However, we believe removing this study permitted a clearer interpretation of our current results.

Our meta-analysis findings agree with the outcome of Balasubramanian et al,[9] who observed increases in mean amplitude and root mean square values in the erector spinae muscle group, indicating lumbar muscle fatigue. The same group also observed vehicle exposure-related changes in the trapezius muscles, with a decrease in median frequency on the right side. Conversely, the authors[15] of a simulator study reported that short-term exposure to vibration had no negative acute effects on fatigue of the upper trapezius muscle. This may speak in some part to the inability of simulators to produce the realistic vibratory environment needed to fatigue the cervical muscles. In addition, the length of exposure time and equipment worn (ie, helmet) in the investigation of Balasubramanian et al[9] also likely contributed to the differences in fatigue outcome measures in the cervical region. The same authors also reported a correlation between pain and flight time ($r^2 = 0.86$) and between right trapezius median frequency fatigue rate and total flying hours ($r^2 = 0.51$). These results further highlight the need for more actual vehicle and aircraft data to help us better understand the influence of vehicle exposure on spinal musculature fatigue and its relationship to injury. Future research into this area is especially important given reports[5,31,32] that have indicated cervical injury is of particular concern to pilots.

Investigations into the effects of vehicle exposure on cervical fatigue should include the helmets worn by pilots and drivers and head-supported mass.[5] The literature[33–35] suggested head-supported mass as a potential injury risk factor. One report[36] indicated that 74% of pilots who wore night-vision goggles experienced neck pain, compared with only 38% of helicopter pilots who did not wear the goggles. The weight of the helmet and other gear supported by the head (eg, night-vision goggles) likely increases the fatigue of the cervical musculature.[37] Further research into the influence of vehicle exposure on the cervical musculature, with and without head-supported mass, may advance our understanding of the interaction among vehicle ride exposure, equipment, and muscle fatigue and its relationship to injury. Research was also inadequate to determine the effects of actual ground-based, rotary-wing, and fixed-wing flight exposure on spinal musculature fatigue. Much work remains to be completed if we are to fully understand the influence of ride exposure in different vehicles and under different conditions.

This meta-analysis indicates the need for further study to determine if fatigability of the lumbar musculature is an injury risk factor for the development of lower back pain. Furthermore, investigators should also explore if vehicle exposure-induced lumbar fatigue is related to cervical injury or pain. Future authors should assess exposure to specific vehicles and by specific personnel. For example, the exposure of an M1A2 Abrams tank driver is very different from that of a gunner on a Bradley fighting vehicle. Recognizing the unique environment and specific needs of the vehicle and operator and how they relate to injury will be critical to the success of any intervention or injury-prevention program (eg, ergonomic seat design, strengthening or stretching programs). Finally, future researchers should examine if a dose-response relationship exists between military vehicle ride (or flight) time and the development of spinal musculature fatigue, as this may provide greater insight into the amount of ride (or flight) exposure required to elicit spinal musculature fatigue.

Limitations

Limitations to this study include the possibility that not all available data (published or unpublished) were included. However, the average fail-safe N was 77 negative data points to negate the significant effect of vehicle exposure on the fatigue of the spinal musculature. Additionally, our funnel plot was asymmetric, indicating the possibility of a publication bias. Nevertheless, a skewed funnel plot may result from factors other than publication bias, such as the smaller sample sizes of certain included studies, choice of effect measure, and chance.[38–40] Given that other factors may have contributed to the asymmetric funnel plot, we chose to include all available data from all known published studies meeting the inclusion criteria, regardless of perceived quality

A limited number of studies met our inclusion criteria. Also, point estimates and CIs may provide false assurances when using an unweighted random-effects model.[19] Therefore, per Borenstein et al,[21] we have provided the separate effects for each datum point (see Supplemental Table, available online at http://dx.doi.org/10.4085/1062-6050-51.9.13.S1). The lack of military-specific studies meeting our inclusion criteria required us to generalize some findings to warfighters. Yet the inclusion of studies in which civilians were exposed to similar vehicle-related forces provides important data to guide future research in this area. Finally, the moderated analyses represented regions of the spine, not specific muscles. Individual muscles in the region may respond differently.

We identified several important gaps in the literature. First, more studies are needed to investigate the effects of actual vehicle exposure on muscular fatigue in each region of the spine. Second, investigations using simulators should mimic the actual ride signature for specific military ground-based vehicles and aircraft. The present meta-analysis included only 1 such study.[25] Third, future authors should explore the effects of vehicle exposure on the fatigue of the spinal musculature in all onboard vehicle personnel. Personnel seated or standing in various locations in a vehicle will likely experience different ride qualities than the driver or pilot. Fourth, the effect of equipment and head-supported mass must be determined. Finally, we need research not only on acute exposures but also on chronic exposures to replicate the daily and weekly deployment exposures of our military warfighters.

This meta-analysis revealed that vehicle exposure increased fatigue in the musculature of the lumbar spine. Research specific to vehicle exposure and in-vehicle testing in the military population was lacking. Future investigators should address these gaps in the literature.

ACKNOWLEDGMENTS

The US Army Aeromedical Research Laboratory-Volunteer Investigations for Mounted and Head-Supported Mass in Dismounted Operations–TCN no. 11010 funded this study. The

results of the present study do not constitute endorsement by the Department of Defense or the US Army Aeromedical Research Laboratory.

REFERENCES

1. Nindl BC, Williams TJ, Deuster PA, Butler NL, Jones BH. Strategies for optimizing military physical readiness and preventing musculoskeletal injuries in the 21st century. *US Army Med Dep J*. 2013; Oct–Dec:5–23.
2. Kasin JI, Mansfield N, Wagstaff A. Whole body vibration in helicopters: risk assessment in relation to low back pain. *Aviat Space Environ Med*. 2011;82(8):790–796.
3. McCrary BF, Van Syoc DL. Permanent flying disqualifications of USAF pilots and navigators (1995–1999). *Aviat Space Environ Med*. 2002;73(11):1117–1121.
4. Truszczynska A, Lewkowicz R, Truszczynski O, Rapala K, Wojtkowiak M. Back pain in Polish military helicopter pilots. *Int J Occup Med Environ Health*. 2012;25(3):258–264.
5. Kollock R, Games K, Wilson AE, Sefton JM. Effects of vehicle-ride exposure on cervical pathology: a meta-analysis. *Ind Health*. 2015; 53(3):197–205.
6. Grossman A, Nakdimon I, Chapnik L, Levy Y. Back symptoms in aviators flying different aircraft. *Aviat Space Environ Med*. 2012; 83(7):702–705.
7. Landau DA, Chapnick L, Yoffe N, Azaria B, Goldstein L, Atar E. Cervical and lumbar MRI findings in aviators as a function of aircraft type. *Aviat Space Environ Med*. 2006;77(11):1158–1161.
8. Wagstaff AS, Jahr KI, Rodskier S. +Gz-induced spinal symptoms in fighter pilots: operational and individual associated factors. *Aviat Space Environ Med*. 2012;83(11):1092–1096.
9. Balasubramanian V, Dutt A, Rai S. Analysis of muscle fatigue in helicopter pilots. *Appl Ergon*. 2011;42(6):913–918.
10. Harrison MF, Neary JP, Albert WJ, et al. Measuring neuromuscular fatigue in cervical spinal musculature of military helicopter aircrew. *Mil Med*. 2009;174(11):1183–1189.
11. Edmondston S, Björnsdóttir G, Pálsson T, Solgård H, Ussing K, Allison G. Endurance and fatigue characteristics of the neck flexor and extensor muscles during isometric tests in patients with postural neck pain. *Manual Ther*. 2011;16(4):332–338.
12. Santos BR, Larivière C, Delisle A, Plamondon A, Boileau PÉ, Imbeau D. A laboratory study to quantify the biomechanical responses to whole-body vibration: the influence on balance, reflex response, muscular activity and fatigue. *Int J Ind Ergonom*. 2008; 38(7–8):626–639.
13. Granata KP, Gottipati P. Fatigue influences the dynamic stability of the torso. *Ergonomics*. 2008;51(8):1258–1271.
14. Moorhouse KM, Granata KP. Role of reflex dynamics in spinal stability: intrinsic muscle stiffness alone is insufficient for stability. *J Biomech*. 2007;40(5):1058–1065.
15. Astrom C, Lindkvist M, Burstrom L, Sundelin G, Karlsson JS. Changes in EMG activity in the upper trapezius muscle due to local vibration exposure. *J Electromyogr Kinesiol*. 2009;19(3):407–415.
16. Li ZY, Jiao K, Chen M, Wang CT, Yang YS. Spectral analysis of electromyography of low back muscle fatigue induced by simulated driving [in Chinese]. *Zhongua Lao Dong Wei Sheng Zhi Ye Bing Za Zhi*. 2003;21(5):365–367.
17. de Oliveira CG, Nadal J. Back muscle EMG of helicopter pilots in flight: effects of fatigue, vibration, and posture. *Aviat Space Environ Med*. 2004;75(4):317–322.
18. Moher D, Liberati A, Tetzlaff J, Altman DG, PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *J Clin Epidemiol*. 2009;62(10):1006–1012.
19. Cameron B, Morrison J, Brammer A. *Development of a Standard for the Health Hazard Assessment of Mechanical Shock and Repeated Impact in Army Vehicles – Final Report*. Vancouver, Canada: BC Research Inc for US Army Medical Research and Materiel Command Contract Report No. DAMD17-91-C-1115, Fort Detrick, MD; 1997.
20. Hansson T, Magnusson M, Broman H. Back muscle fatigue and seated whole body vibrations: an experimental study in man. *Clin Biomech (Bristol, Avon)*. 1991;6(3):173–178.
21. Borenstein M, Hedges LV, Higgins JPT, Rothstein HR. *Introduction to Meta-Analysis*. Chichester, UK: John Wiley & Sons; 2009.
22. Rosenthal R. The file drawer problem and tolerance for null results. *Psychol Bull*. 1979;86(3):638–641.
23. Viechtbauer R. Package 'metafor'. Meta-Analysis Package for R. C Ran Project Web site. http://cran.r-project.org/web/packages/metafor/metafor.pdf. Accessed July 20, 2016.
24. Orwin RG. A fail-safe N for effect size in meta-analysis. *J Educ Stat*. 1983;8(2):157–159.
25. Cameron B, Morrison J, Robinson D, Vukusic A, Martin S, Roddan G. *Development of a Standard for the Health Hazard Assessment of Mechanical Shock and Repeated Impact in Army Vehicles: Phase 4 Experimental Phase*. Vancouver, Canada: BC Research Inc and John P. Albano Aircrew Protection Division for the US Army Aeromedical Research Laboratory, Fort Rucker, AL; 1996.
26. De Luca CJ. Myoelectrical manifestations of localized muscular fatigue in humans. *Crit Rev Biomed Eng*. 1984;11(4):251–279.
27. Merletti R, Knaflitz M, DeLuca CJ. Electrically evoked myoelectric signals. *Crit Rev Biomed Eng*. 1992;19(4):293–340.
28. Dimitrova NA, Dimitrov GV. Interpretation of EMG changes with fatigue: facts, pitfalls, and fallacies. *J Electromyogr Kinesiol*. 2003; 13(1):13–36.
29. Hagg GM, Luttmann A, Jager M. Methodologies for evaluating electromyographic field data in ergonomics. *J Electromyogr Kinesiol*. 2000;10(5):301–312.
30. Cifrek M, Medved V, Tonkovic S, Ostojic S. Surface EMG based muscle fatigue evaluation in biomechanics. *Clin Biomech (Bristol, Avon)*. 2009;24(4):327–340.
31. Aydog ST, Turbedar E, Demirel AH, Tetik O, Akin A, Doral MN. Cervical and lumbar spinal changes diagnosed in four-view radiographs of 732 military pilots. *Aviat Space Environ Med*. 2004; 75(2):154–157.
32. De Loose V, Van den Oord M, Burnotte F, et al. Individual, work-, and flight-related issues in F-16 pilots reporting neck pain. *Aviat Space Environ Med*. 2008;79(8):779–783.
33. Lange B, Torp-Svendsen J, Toft P. Neck pain among fighter pilots after the introduction of the JHMCS helmet and NVG in their environment. *Aviat Space Environ Med*. 2011;82(5):559–563.
34. Manoogian SJ, Kennedy EA, Duma SM. *A Literature Review of Musculoskeletal Injuries to the Human Neck and the Effects of Head-Supported Mass Worn by Soldiers*. Fort Rucker, AL; US Army Aeromedical Research Laboratory; 2005. US Army Aeromedical Research Laboratory Contract Report No. CR-2006-01.
35. Merkle AC, Kleinberger M, Uy OM. The effects of head-supported mass on the risk of neck injury in army personnel. *Johns Hopkins APL Tech Dig*. 2005;26(1):75–83.
36. Äng B, Harms-Ringdahl K. Neck pain and related disability in helicopter pilots: a survey of prevalence and risk factors. *Aviat Space Environ Med*. 2006;77(7):713–719.

37. Thuresson M, Ang B, Linder J, Harms-Ringdahl K. Neck muscle activity in helicopter pilots: effect of position and helmet-mounted equipment. *Aviat Space Environ Med*. 2003;74(5):527–532.

38. Mller AP, Jennions MD. Testing and adjusting for publication bias. *Trends Ecol Evol*. 2001;16(10):580–586.

39. Egger M, Davey Smith G, Schneider M, Minder C. Bias in meta-analysis detected by a simple, graphical test. *BMJ*. 1997;315(7109): 629–634.

40. Stern JM, Simes RJ. Publication bias: evidence of delayed publication in a cohort study of clinical research projects. *BMJ*. 1997;315(7109):640–645.

Address correspondence to Roger O. Kollock, PhD, ATC, CSCS, Department of Kinesiology and Rehabilitative Sciences, The University of Tulsa, 1215 South Boulder Avenue, Tulsa, OK 74104. Address e-mail to roger-kollock@utulsa.edu.