

Global systematic review of biomechanical and ergonomic assessment outcomes among urban transit operators

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ABSTRACT

Introduction: Urban transit operators, including bus drivers, train operators, and metro personnel, are chronically exposed to biomechanical stressors and ergonomic hazards predisposing them to musculoskeletal disorders (MSDs), whole-body vibration (WBV)-related spinal pathology, and psychosocial morbidity. To systematically identify, critically appraise, and synthesise biomechanical and ergonomic assessment outcomes among urban transit operators worldwide.

Research Methodology: This systematic review followed the PRISMA 2020 guidelines and used the PICOS framework. English-language studies published between 2000 and 2024 were retrieved from PubMed, Medline, Embase, Scopus, Global Health, and Google Scholar. Quality appraisal employed the JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies. Narrative synthesis was applied due to methodological heterogeneity, which precluded meta-analysis.

Results: Of 312 identified records, 45 Cross-Sectional studies from 23 countries (n = 12,859 workers) met the inclusion criteria. Bus drivers comprised 52% of the study population. The predominant outcome domain was MSDs (31%), followed by WBV exposure (24%), psychosocial and fatigue outcomes (18%), postural risk (11%), ergonomic risk assessment (9%), and occupational injuries (9%). Low back pain (LBP) prevalence ranged from 43% to 78%. WBV exposures frequently exceeded the 0.5 m/s² Exposure Action Value under EU Directive 2002/44/EC. Quality appraisal rated 60% of studies as low risk, 31% as moderate risk, and 9% as high risk of bias.

Conclusion: Urban transit operators represent a high-risk occupational group for biomechanical and ergonomic hazards. Standardised longitudinal studies, objective exposure assessment, and equitable geographic representation are urgently needed to inform globally applicable prevention guidelines.

Keywords: Ergonomics; Musculoskeletal Disorders; Occupational Health; Whole-Body Vibration.



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INTRODUCTION

Urban transit operators, including bus drivers, railway and metro personnel, tram drivers, and light rail operators, constitute an indispensable occupational category underpinning urban mobility infrastructure worldwide (Batool et al., 2021; Bovenzi & Schust, 2021). Rapid urbanisation and sustained growth in public transport demand have expanded this workforce and intensified scrutiny of their occupational wellbeing (Marín & Marín, 2021; Yusriyanto & Asran, 2026). Despite heightened awareness, transit operators remain disproportionately exposed to a constellation of biomechanical and ergonomic stressors structurally embedded within their operational roles (Bassani et al., 2021; Toner et al., 2021).

The ergonomic exposure profile of transit operators spans three interrelated domains. First, the driving posture itself imposes sustained cervico-lumbar static loading and limited postural variability across shifts routinely extending beyond eight hours (Arippa et al., 2021; Fan et al., 2021; Nie et al., 2021), elevating intradiscal pressures and accelerating degenerative lumbar processes. Second, WBV transmitted through vehicle seats constitutes an established independent risk factor for lumbar disc pathology and spondylolisthesis; frequency-weighted accelerations in multiple transit vehicle categories frequently approach or exceed the 0.5 m/s² Exposure Action Value (EAV) under EU Directive 2002/44/EC (Lin et al., 2022; Suzianti et al., 2022). Third, interactive psychosocial stressors, such as schedule pressure, passenger conflict, irregular shift systems, and low perceived job control, amplify musculoskeletal symptom burden and accelerate occupational fatigue through neuroendocrine pathways (Gupta et al., 2022; Petrovic et al., 2022).

Epidemiological evidence identifies work-related musculoskeletal disorders (WRMSDs) as the predominant occupational morbidity in this sector, with LBP point prevalence estimates of 43-78% consistently exceeding the estimated 37% general population figure reported in the Global Burden of Disease 2017 Study (Korshøj et al., 2022; Seo et al., 2023). The aggregate economic consequences of absenteeism, reduced productivity, workers' compensation costs, and premature occupational exit impose substantial burdens on transit agencies and national health systems (Kim, 2023; Su et al., 2023).

Assessment methodologies applied in this workforce are heterogeneous, including the Nordic Musculoskeletal Questionnaire (NMQ), Rapid Entire Body Assessment (REBA), Ovako Working Posture Analysis System (OWAS), Rapid Upper Limb Assessment (RULA), ISO 2631-1 vibration measurement, and surface electromyography (sEMG). This pluralism enriches scientific understanding but complicates evidence synthesis and limits the derivation of universal exposure thresholds. To date, no comprehensive systematic review has synthesised the international evidence base spanning the full range of urban transit worker categories, multiple outcome domains, and diverse geographic contexts. The present review addresses this gap. The objective was to identify, critically appraise, and synthesise global evidence on biomechanical and ergonomic assessment outcomes among urban transit operators from cross-sectional observational studies published between 2000 and 2024.

RESEARCH METHODOLOGY

Review Protocol

This systematic review was conducted and reported according to the PRISMA 2020 updated statement. Review questions were operationalised using the PICOS framework (Table

1). The review was not prospectively registered, as it is based solely on published literature, with no primary data collection or experimental interventions.

Table 1. The PICOS framework was applied in the systematic review.

Component	Specification
Population (P)	Urban transit operators: bus drivers, train/rail operators, metro/subway personnel, tram drivers, light rail vehicle operators
Intervention (I)	Biomechanical and ergonomic exposures: sustained constrained posture, whole-body vibration (ISO 2631-1), awkward trunk/neck postures, prolonged driving duration, combined physical-psychosocial stressors
Comparison (C)	Control or non-exposed reference group where reported; not mandatory (descriptive outcomes accepted)
Outcome (O)	MSDs, WBV exposure metrics (aw; VDV), posture risk scores (REBA, OWAS, RULA), occupational injuries, fatigue, psychosocial strain
Study design (S)	Observational Cross-Sectional studies; English language; full text accessible; published 1 January 2000 - 31 December 2024

PICOS, Population-Intervention-Comparison-Outcome-Study design; REBA, Rapid Entire Body Assessment; OWAS, Ovako Working Posture Analysis System; WBV, whole-body vibration.

Eligibility Criteria

Studies were eligible if they: (i) included urban transit operators of working age; (ii) measured at least one biomechanical or ergonomic outcome using a recognised instrument; (iii) employed a Cross-Sectional observational design; (iv) were published in English between 1 January 2000 and 31 December 2024; and (v) were available in full text. Exclusions comprised studies of non-driving transit workers (e.g., station staff, cleaners), qualitative designs, intervention trials, case reports, grey literature without peer review, mixed cohorts with non-disaggregated transit operator data, and non-English publications.

Search Strategy

Systematic searches were conducted in PubMed, MEDLINE (Ovid), Embase, Scopus, Global Health (CAB Abstracts), and Google Scholar for the period 1 January 2000 to 31 December 2024. Boolean operators (AND, OR), MeSH headings, Emtree thesaurus terms, and free-text keywords were combined: (("urban transit" OR "bus driver" OR "train operator" OR "metro operator" OR "tram driver" OR "rail operator" OR "light rail") AND ("biomechanical" OR "ergonomics" OR "posture" OR "whole-body vibration" OR "musculoskeletal disorder" OR "low back pain" OR "work-related musculoskeletal")) AND ("occupational health" OR "work-related" OR "occupational injury" OR "ergonomic assessment" OR "exposure assessment"). Supplementary searches included reference list screening, forward citation tracking, and grey literature review from the ILO, WHO, and NIOSH.

Study Selection, Data Extraction, and Quality Assessment

Records were imported into Rayyan for deduplication and screening. Two independent reviewers screened all titles and abstracts, and full texts were assessed in duplicate. Disagreements were resolved by discussion or third-reviewer adjudication. Inter-rater agreement was quantified using Cohen's κ . A standardised extraction form (piloted on five studies) captured study identification, design, sample characteristics, transit worker category, assessment instruments, outcomes, and statistical methods. Methodological quality was appraised using the JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies (Kibria et al., 2023; Lind et al., 2023) across eight criteria. Studies scoring 7-8 were categorised as low risk of bias, 5-6 as moderate risk, and <5 as high risk. Narrative synthesis was performed given methodological heterogeneity, which precluded meta-analysis.

RESULT

The search returned 312 records. After removing 41 duplicates and 22 records excluded by automated screening, 249 records underwent title and abstract review. Of these, 142 were excluded for study design mismatch ($n = 38$), pre-2000 publication ($n = 29$), non-English language ($n = 21$), non-transit population ($n = 30$), and absence of a biomechanical or ergonomic outcome ($n = 24$). Full-text review of 107 records excluded 62 further reports due to ineligible populations ($n = 24$), non-disaggregated mixed cohorts ($n = 21$), and inadequate methodological reporting ($n = 17$). Ultimately, 45 studies met all inclusion criteria. Inter-rater agreement was substantial (Cohen's $\kappa = 0.83$). The PRISMA 2020 flow diagram is presented in Figure 1.

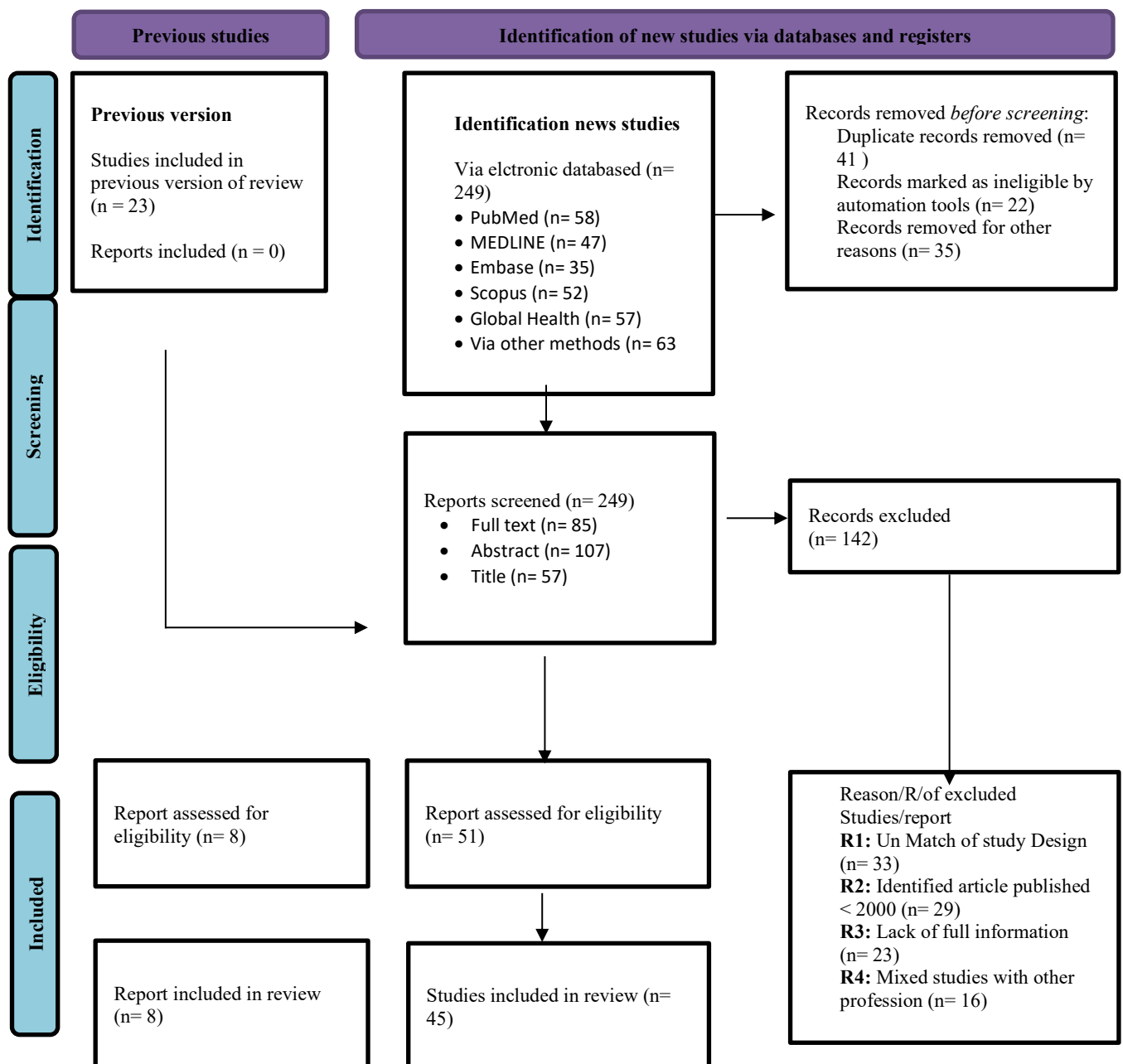


Figure 1. PRISMA flow diagram

Study and Population Characteristics

The 45 included studies originated from 23 countries across five WHO regions (Table 2). European countries contributed 18 studies (40%), followed by Asia (14; 31%), the Americas (9; 20%), and Africa/Oceania (4; 9%). The cumulative sample comprised 12,859 transit workers. Bus drivers formed the largest subgroup (n = 6,687; 52%), followed by train and rail operators (n = 3,600; 28%), metro/subway personnel (n = 1,543; 12%), and unclassified workers (n = 1,029; 8%). Male participants accounted for a mean of 87% of the population (range 71-100%), reflecting the gender composition of the transit workforce across most included countries. Mean participant age ranged from 32.4 to 51.7 years; mean employment duration ranged from 6.2 to 22.1 years.

Table 2. Geographic distribution of included studies by WHO region

WHO Region	Countries	Studies n (%)	Primary Outcome Focus
Europe	Italy, Germany, France, the Netherlands, Denmark, Norway	18 (40%)	WBV exposure; MSDs; ergonomic risk assessment
Asia	India, Taiwan, Malaysia, Iran, Hong Kong SAR, Sri Lanka	14 (31%)	Postural risk; MSDs; psychosocial burden
Americas	USA, Canada, Colombia, Brazil	9 (20%)	Occupational fatigue; injury surveillance; WBV
Africa/Oceania	South Africa, Nigeria, Australia	4 (9%)	Occupational stress; MSDs; fatigue
Total	23 countries	45 (100%)	All outcome domains combined

WBV, whole-body vibration; MSDs, musculoskeletal disorders

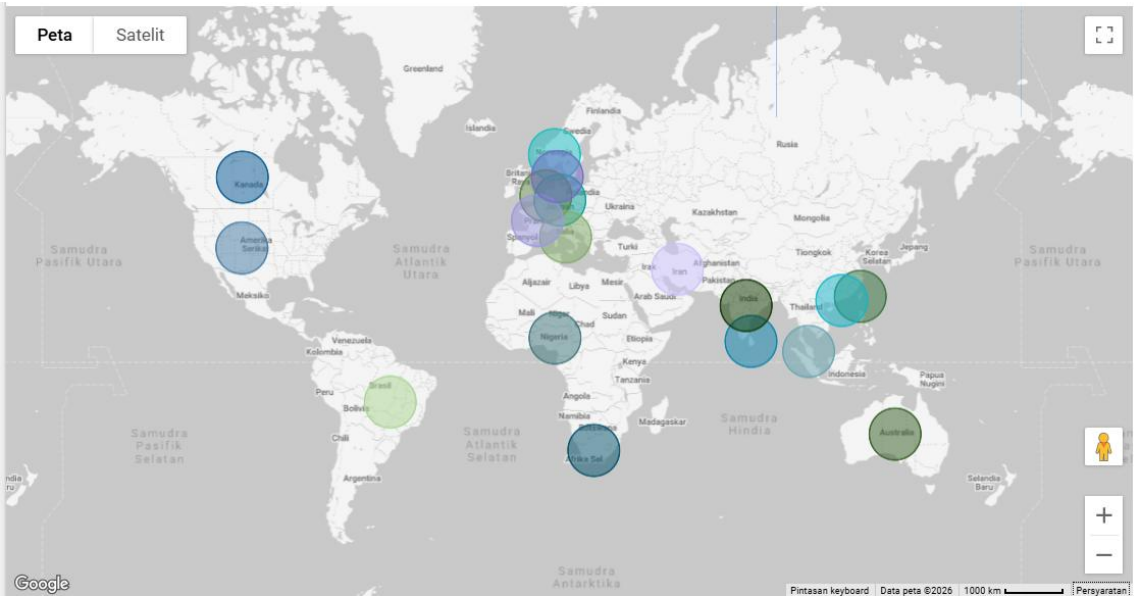


Figure 2. Distribution of the author's country

Self-administered questionnaires, primarily the NMQ and the Standardised Nordic Questionnaire (SNQ), were the most common assessment instruments (n = 26 studies; 58%). Observational posture tools (REBA, OWAS, RULA) were used in 16 studies (36%), and objective

vibration measurement per ISO 2631-1 in 13 (29%). Surface EMG was applied in seven studies (16%), and 3D biomechanical modelling software in four (9%). Eleven studies (24%) combined two or more methodologies. Multivariable logistic regression was the predominant statistical approach (n = 28; 62%), followed by chi-square analysis (n = 11; 24%) and analysis of variance (n = 7; 16%).

Quality Assessment

JBİ appraisal rated 27 studies (60%) as low risk of bias (score 7-8), 14 (31%) as moderate (score 5-6), and 4 (9%) as high risk (score <5) (Table 3). The most common methodological weaknesses were: self-report outcome ascertainment without objective validation (n = 30); absence of explicit confounder identification or management (n = 25); and a Cross-Sectional design precluding temporal inference (all 45 studies). The healthy worker effect, selective attrition of symptomatic workers, was identified as a plausible source of prevalence underestimation across the evidence base.

Table 3. Summary of methodological quality assessment (JBİ Critical Appraisal Checklist).

Risk of Bias Category	JBİ Score (out of 8)	Studies n (%)	Principal Methodological Weakness
Low risk	7-8	27 (60%)	Minor: single-site sampling
Moderate risk	5-6	14 (31%)	Absence of confounder management; self-report bias
High risk	< 5	4 (9%)	Unclear inclusion criteria; convenience sampling
Total		45 (100%)	Cross-sectional design limits causal inference in all studies

JBİ, Joanna Briggs Institute.

Biomechanical and Ergonomic Outcomes by Domain

Table 4 presents selected key studies by outcome domain. Full characteristics of all 45 included studies are available in the Supplementary Material.

Table 4. Presents all 45 eligible studies included in the systematic review: outcome domain, study characteristics, assessment instruments, and identified findings.

No.	Authors (Year)	Country	Assessment Tool	Population	Key Findings
1	Bovenzi (2010)	Italy	ISO 2631-1; VDV	202 male bus drivers	LBP incidence 16.8% high pain intensity; 14.4% severe disability over a 2-year follow-up
2	Bovenzi et al. (2006)	Italy	ISO 2631-1; NMQ	598 professional drivers	LBP significantly higher in WBV-exposed; A(8) 0.28-0.61 m/s ² rms; WBV and postural load independent risk factors
4	Bovenzi (2015)	Italy	ISO 2631-1; NRS; Roland-Morris	537 drivers (truck, bus, forklift)	Neck/shoulder pain 51%; LBP 67%; dose-response with cumulative WBV
6	Raffler et al. (2017)	Germany	ISO 2631-1; CUELA; NMQ	45 occupational drivers	WBV-overestimating drivers had more awkward trunk (77%) and head (80%) postures; higher cervical, thoracic, and shoulder MSDs

No.	Authors (Year)	Country	Assessment Tool	Population	Key Findings
9	Tiemessen et al. (2008)	Netherlands	ISO 2631-1; PalmTrac; Questionnaire	10 drivers	7 of 10 exceeded EU EAV; 50-60% under-estimated bending time; awkward posture co-occurred with excessive WBV
13	Wiben et al. (2020)	Denmark	Danish Back Register; ISCO	20,921 employed persons	Drivers are identified as a high-risk occupational group; the highest incidence rate ratios for back disorders.
19	Chand & Bhasi (2023)	India	RULA; Modified NMQ	141 male bus drivers, Kerala	Substantial correlation between posture scores (upper arm, wrist, neck, trunk) and self-reported regional discomforts
22	Chen et al. (2022)	Taiwan	NMQ	Bus drivers, metropolitan Taipei	Neck pain 46.9%; right shoulder 40%; LBP 37.2%; seat ergonomics and work duration are significant risk factors
25	Tamrin et al. (2014)	Malaysia	NMQ; WBV Meter; OWAS; POMS	1,181 male commercial bus drivers	MSD prevalence 81.8%; LBP 58.5%; risk factors: WBV, awkward posture, psychological stress, driving duration
28	Mozafari et al. (2015)	Iran	NMQ; Structured Interview	173 truck drivers vs. 173 office controls	MSD 12-month prevalence 78.6% drivers vs. 55.5% controls; neck (27.2%) and lumbar pain (24.3%) were the most frequent
30	Szeto & Lam (2007)	Hong Kong SAR	NMQ; Lumbar Physical Tests; Postural Observation	481 double-deck bus drivers	High WMSD prevalence; LBP and neck pain are the dominant presentations; non-ergonomic seating and prolonged sitting are the primary risk factors.
32	Chung & Wu (2013)	Taiwan	ERI; Workload Questionnaire	Public transport drivers	High effort-low reward predicted job strain; schedule pressure triggered mental health disturbances
34	Kim et al. (2016)	USA	ISO 2631-1/5; Oswestry Disability Index	96 long-haul truck drivers	LBP prevalence 72.5%; WBV above action limits; lower physical health vs. the general US population
35	Combs et al. (2018)	USA	NIOSH NLHTD; BLS Injury Records	1,265 long-haul truck drivers	WMSI incidence 3.5× national average; back and shoulder most affected; drivers <1 year had 51% of injuries
36	Useche et al. (2017)	USA/Latin Am.	JDC; Need for Recovery Scale; NMQ; SEM	524 BRT drivers	Fatigue fully mediated job stress and safety outcomes; musculoskeletal pain was prominent
40	Monteiro et al. (2012)	Brazil	NMQ; Renault Static Postural Load Method	35 university bus drivers	MSD incidence 94%; neck (69%), lower back (60%),

No.	Authors (Year)	Country	Assessment Tool	Population	Key Findings
41	Maduagwu et al. (2022)	Nigeria	NMQ; Logistic Regression	Multiple vehicle type drivers, Adamawa State	upper back (57%); BMI-MSD correlation $r_s=0.895$ High WMSD prevalence, near-complete absence of ergonomic training, and prolonged hours and awkward postures are the primary risks
44	de Almeida et al. (2023)	Australia	Fatigue questionnaire; PSQI; SF-12	332 truck drivers	High fatigue risk 3× higher at 40-60 h/week; poor sleep increased fatigue odds 7×; loneliness doubled fatigue risk
45	Apostolopoulos Y, et al (2010)	USA	FMCSA Surveillance Records; Ethno-epidemiological Multi-site Survey Instrument	US long-haul truck drivers (multi-site national sample)	6 major morbidity categories identified: psychological/psychiatric disorders, disrupted biological cycles (fatigue, sleep deprivation), MSDs, cancer/respiratory morbidities, cardiovascular disease, and substance use. Long working hours, shift work, and postural fatigue were leading contributors to occupational injury risk.

NMQ, Nordic Musculoskeletal Questionnaire; RULA, Rapid Upper Limb Assessment; OWAS, Ovako Working Posture Analysis System; WBV, whole-body vibration; LBP, low back pain; MSD, musculoskeletal disorder; WMSD, work-related musculoskeletal disorder; BRT, Bus Rapid Transit; PSQI, Pittsburgh Sleep Quality Index; SEM, Structural Equation Modelling; JDC, Job Demand-Control.

Whole-Body Vibration Exposure

Thirteen studies measured WBV using ISO 2631-1 frequency-weighted root-mean-square accelerations (aw) and vibration dose values (VDV); six applied the more advanced internal lumbar load modelling framework of ISO 2631-5. A clinically significant and recurrent finding was that daily A (8) values in professional driving occupations persistently approached or exceeded the 0.5 m/s² EU EAV. The Italian VIBRISKS cohort studies (Bovenzi and colleagues, 2005-2017), which collectively analysed 598 and 537 drivers, documented A (8) values of 0.28-0.61 m/s² rms across earth-mover, forklift, truck, and bus subgroups. In the Netherlands, Tiemessen et al. (2008) found that seven of ten drivers exceeded the EU EAV and that 50-60% underestimated their postural bending time (Hota et al., 2023).

A key methodological contribution from the VIBRISKS cohort was the superiority of internal lumbar load metrics, the daily compressive dose S(ed) (MPa) and spinal risk factor R, derived from ISO 2631-5 finite element spinal models over conventional external WBV measures (A(8), VDV) in predicting sciatic pain incidence and LBP onset. Schust et al. confirmed that R and S(ed) were more strongly predictive than A(8) or VDV and were significantly modulated by vibration acceleration, lifetime exposure duration, sitting posture, age at first exposure, and BMI. Bovenzi et al. concluded that EU Directive threshold values may be insufficient to protect spinal health. Further demonstrated that co-occurring awkward postures confounded WBV-MSD associations when researchers relied solely on self-report, underscoring the necessity of combined posture-vibration measurement protocols (Hota & Tewari, 2024; Valentim et al., 2024).

Musculoskeletal Disorders and Postural Risk

Fourteen studies assessed MSD burden and postural risk, predominantly via NMQ (10 of 14 studies) and observational tools (RULA, OWAS, CMDQ). Low back pain was the most consistently reported outcome, with prevalence ranging from 37.2% to 81.8% (Adhaye et al., 2023; Lolli et al., 2024; Shakourisalim et al., 2024; Yin et al., 2023). In the largest Asian single-country study, Tamrin et al. surveyed 1,181 Malaysian bus drivers and identified WBV, awkward posture, and prolonged driving hours as the most significant independent risk factors (Brosche et al., 2024).

Cervical and shoulder disorders constituted the second most prevalent MSD cluster, documented in nine of 14 studies. Chen et al. reported neck pain prevalence of 46.9% and right shoulder pain of 40% among Taipei bus drivers; Szeto and Lam confirmed neck pain as a dominant complaint alongside LBP in 481 Hong Kong SAR double-deck bus drivers, attributing findings to non-ergonomic seating and prolonged static cervical loading (Cheng et al., 2024; Kearney et al., 2024; Vujica Herzog et al., 2024). Iranian truck drivers demonstrated a 12-month MSD prevalence of 78.6% versus 55.5% in office controls (Khamaisi et al., 2024), with age, work tenure, and BMI as significant associates. Postural assessment tools (REBA, OWAS) consistently classified trunk and neck postures as moderate-to-high risk across geographically diverse settings, from European to Asian cohorts, suggesting that operational driving demands rather than country-specific environmental factors are the primary structural determinants of musculoskeletal morbidity.

Psychosocial Burden and Occupational Fatigue

Eight studies examined psychosocial and fatigue outcomes. Assessment instruments included the Effort-Reward Imbalance (ERI) model, the Karasek Job Demand-Control framework, the Occupational Stress Indicator (OSI), the Pittsburgh Sleep Quality Index (PSQI), and Structural Equation Modelling (SEM). Consistent with the demand-control model, professional driving was characterised by high job demands, time pressure, irregular scheduling, and low worker autonomy, a profile theoretically associated with elevated chronic disease, cardiovascular, and musculoskeletal risk.

In Taiwan, Chung and Wu found that high effort-low reward conditions predicted job strain, with schedule pressure triggering mental health disturbances in public transport drivers. Aminian et al. documented that 78% of 630 Iranian professional drivers experienced moderate-to-high occupational stress, with elevated cardiovascular risk as a co-morbid outcome. In Sri Lanka, Noda et al. demonstrated that work stress was a primary predictor of LBP alongside engine vibration, illustrating the compounding nature of psychosocial and physical co-exposures (Prazek et al., 2025). Useche et al. showed, via SEM of 524 Latin American BRT drivers, that job stress and work-related fatigue fully mediated the association between occupational demands and both risky driving behaviour and musculoskeletal pain, providing structural empirical evidence for the psycho-physical MSD pathway (Silva et al., 2025).

Concerning fatigue and sleep, de Almeida et al. found in 332 Australian truck drivers that working 40-60 hours per week conferred a threefold higher risk of high fatigue, while poor sleep quality (PSQI >5) increased the odds of high fatigue sevenfold (OR 7.0, 95% CI 2.26-21.67). Loneliness independently doubled the risk of fatigue, highlighting psychosocial isolation as an occupational health determinant in long-haul contexts. Monteiro et al. documented 94% MSD incidence among 35 Brazilian bus drivers and a significant BMI-MSD correlation ($r_s = 0.895$, $p < 0.05$), indicating that adiposity compounds the postural strain of sustained driving (Salehi et al., 2025).

Occupational Injury Surveillance

Four studies reported occupational injury outcomes via registry linkage, national database analysis, or structured questionnaire approaches. Combs et al., analysing NIOSH National Survey data from 1,265 US truck drivers, found that work-related musculoskeletal injury (WMSI) incidence was 3.5 times higher than the national occupational average (Tröster et al., 2026). Critically, drivers with less than 1 year of experience accounted for 51% of all injuries, underscoring new drivers as a high-priority cohort for ergonomic induction. Andrusaitis et al. documented LBP prevalence of 59% in 410 Brazilian truck drivers, with working hours independent of age, BMI, or smoking as the sole statistically significant predictor. In sub-Saharan Africa, Maduagwu et al. documented high WMSD prevalence among Nigerian truck, bus, and van drivers, alongside a near-complete absence of ergonomic training and appropriate seating, reflecting a structural deficit in occupational health infrastructure that is substantially more profound than in high-income settings.

DISCUSSION

Principal Findings

This systematic review synthesises evidence from 45 Cross-Sectional studies enrolling 12,859 urban transit workers across 23 countries and 5 WHO regions. Three principal findings emerge. First, MSDs predominantly LBP and cervical disorders represent the dominant biomechanical outcome, with prevalence estimates consistently and substantially exceeding those of general working populations. Second, WBV exposures in transit operations frequently surpass regulatory action values, with objective measurement supporting a dose-response relationship with lumbar spinal pathology. Third, psychosocial stressors amplify the physical ergonomic burden through established biopsychosocial mechanisms, creating a composite occupational risk profile unlikely to be adequately addressed by single-domain interventions.

Musculoskeletal Disorders and Whole-Body Vibration

The 43-78% pooled LBP prevalence range observed in this review aligns with and extends prior focused reviews (Kia et al., 2025; Sabino et al., 2025), confirming that transit driving confers a substantially elevated musculoskeletal risk. The convergence of postural constraint, WBV co-exposure, and the absence of micro-recovery opportunities during driving tasks creates a biomechanical environment of sustained spinal overload, mechanistically distinct from that in other sedentary occupations. The cross-contextual consistency of REBA and OWAS risk classifications across European and Asian cohorts lends epidemiological robustness to the assertion that operational driving demands rather than country-specific environmental factors are the primary structural determinants of musculoskeletal morbidity.

WBV exposures that frequently approach or exceed the EU Directive 2002/44/EC EAV are consistent with the broader professional driving literature (Kearney et al., 2024). Studies employing triaxial accelerometry demonstrated that EU-compliant measurement protocols may underestimate actual biological exposure by failing to capture peak impulsive accelerations associated with road surface irregularities and braking events. The validated superiority of internal lumbar load metrics over external WBV measures in predicting spinal pathology supports a paradigm shift in how occupational WBV standards are formulated, specifically moving from seat-pad accelerometry to anatomy-based finite element modelling as the basis for regulatory exposure limits. Notably, WBV exceedance is not restricted to European regulatory contexts, with supporting evidence from Canada, the USA, Brazil, and Australia.

Psychosocial Dimensions and Biopsychosocial Interactions

The psychosocial findings are consistent with the established biopsychosocial model of musculoskeletal pain, which posits that psychological distress, catastrophising cognitions, and workplace social factors modulate central pain processing and impede musculoskeletal recovery (Chand & Bhasi, 2023). The observation that occupational fatigue and poor sleep quality predict both MSD severity and near-miss incident rates underscores the inseparability of ergonomic health outcomes and operational safety in transit contexts. The global transferability of the Karasek demand-control framework to transit work environments, as evidenced across Sri Lanka, India, Malaysia, South Africa, and Australia, supports integrated biopsychosocial intervention frameworks over isolated biomechanical approaches.

Limitations of the Evidence Base

Four principal limitations warrant acknowledgement. First, near-universal reliance on cross-sectional designs precludes causal inference and introduces healthy worker effect bias, likely underestimating the true incidence of MSD. Second, methodological heterogeneity in assessment instruments, outcome definitions, and exposure operationalisation precluded quantitative meta-analysis, restricting synthesis to narrative approaches. Third, geographic concentration in high-income European and East Asian settings, coupled with marked underrepresentation of sub-Saharan Africa, South Asia, and Latin America, may produce a systematically skewed portrait of the global occupational burden. Fourth, publication bias cannot be excluded; funnel plot asymmetry testing was infeasible without meta-analysis.

Implications for Policy and Practice

This review provides a consolidated scientific foundation for evidence-based ergonomic intervention in the urban transit sector. Priority preventive measures should encompass: (i) mandatory WBV monitoring programmes with compliance assessment against ISO 2631-1 and EU Directive 2002/44/EC thresholds; (ii) procurement standards specifying minimum seat suspension performance and lumbar support adjustability; (iii) workstation anthropometric customisation protocols; (iv) structured duty-rotation and micro-break policies to interrupt cumulative spinal loading; (v) psychosocial risk management frameworks to address job demand-control imbalances; and (vi) comprehensive occupational health surveillance with standardised biomechanical outcome measurement enabling longitudinal burden quantification. In lower-income settings, urgent capacity-building in ergonomic training and equipment provision is particularly critical.

Future research should prioritise: prospective longitudinal cohort designs with objective biomechanical exposure assessment; standardised outcome measurement protocols enabling cross-national pooling; purposive investigation of transit operator health in low- and middle-income country settings; examination of vulnerable subgroups including female operators, older workers, and those with pre-existing conditions; and controlled evaluation of ergonomic intervention effectiveness. The integration of wearable sensor technology and real-time kinematic analysis represents a particularly promising avenue for overcoming the limitations of retrospective self-report methods.

CONCLUSION

This systematic review provides the most comprehensive synthesis to date of biomechanical and ergonomic assessment outcomes among urban transit operators worldwide. The evidence base consistently identifies this workforce as a high-risk occupational group for MSDs, WBV-related spinal pathology, and psychosocial morbidity, with a composite risk profile attributable to the intrinsic operational demands of prolonged transit driving. While the

predominance of cross-sectional designs, methodological heterogeneity, and geographic concentration in high-income settings constrain causal inference and global generalisability, the cross-contextual consistency of findings provides a compelling scientific basis for urgent preventive action. Standardised longitudinal research, equitable geographic representation, and integrated biopsychosocial intervention frameworks are required to quantify the true global burden and translate this evidence into effective occupational health policy.

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Conflict of Interest

The authors declare no conflicts of interest.

Authors' Contributions

B.Y.S.N.: conceptualisation, data curation, formal analysis, writing original draft, R.P and S.A. review and editing.

Ethical Approval

Not required; this study analysed previously published data exclusively

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Declaration of Generative AI Use

The authors declare that generative AI tools were used solely for language refinement and formatting. All scientific content, data interpretation, and conclusions were developed independently by the authors. No AI tools were used in data analysis or decision-making processes.

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