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Helicopter Operational Vibration and Noise: Pilot Exposure Analysis, Health Impact, and Risk Management

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ABSTRACT

Offshore oil and gas operations rely on rotorcraft to transport crew between onshore bases and remote installations. Occupational exposure during these transits generates somatic and cognitive fatigue in flight crews through coupled mechanical and acoustic stressors. This research quantified infrasound and low-frequency acoustic dose, along with whole-body vibration, a primary determinant of fatigue during extended sectors. The objective of this study was to characterize pilot daily whole-body vibration and sound noise dose across full duty periods (≤ 8 h), benchmarking against international occupational health thresholds, through an in-field acquisition using portable triaxial accelerometers and calibrated microphones during commercial offshore operations. Manufacturer specifications and field calculations converged on a cumulative dose exceeding occupational health limits promulgated by safety agencies and normative bodies. Evidence supported operation-specific exposure ceilings to inform duty–rest scheduling, ON/OFF schedules, and fatigue risk management systems trend monitoring within operators.

Keywords: Helicopters; Pilots; Human performance; Human factors engineering; Vibration; Aerodynamic noise.

INTRODUCTION

Human biodynamic response to mechanical loading involves coupled neuromusculoskeletal pathways that remain partially unresolved. Aeronautical technology has outpaced human-factors integration, generating capability–resilience mismatches across operator generations. In rotorcraft, this gap materializes as elevated fatigue risk from whole-body vibration (WBV), acoustic exposure, and sustained cognitive demand during low-altitude flight. Human error persists as the dominant accident precursor in helicopter operations (ICAO 2018; Shappell and Wiegmann 2000) underscoring the need for tighter human–machine–environment coupling in safety system design.

Rotor-wing crews exhibit higher fatigue indices than fixed-wing aviators, driven by persistent airframe vibration, the cognitive load of terrain-contour or low-altitude flights, and the demands of manual control in several touch-and-go operations in offshore installations. Fixed-wing pilots, spared the worst of structural vibration, nevertheless accumulate hazardous noise doses over multi-hour sectors. Empirical evidence links pilot morbidity to WBV and sound-noise (SN) exposure exceeding occupational thresholds. Offshore fleet expansion and a global pilot shortfall intensify rostering pressures, while cockpit automation, though reducing hand-arm vibration (HAV), leaves WBV and SN exposure unabated, with documented long-term sequelae. Despite some advancements, pilot well-being remains a concern, as the aviation sector has been slow to recognize the negative impacts on pilots and their families. Research indicates that pilots' job-related health problems are associated with exposure to prolonged loud noise and excessive vibration, which frequently exceed safety thresholds.

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Research contribution and discussion

Led by an active AW189 offshore pilot, this review synthesizes the literature on rotor-wing crew WBV and SN exposure and associated fatigue and health concerns. It explores exposure characterization methods to control dose and attenuate health sequelae. A normative gap is identified, showcasing empirical data to support safer operational protocols.

Prior research catalogues pilot health impacts from WBV and SN (Lovesey 1979; Seidel *et al.* 1980; Gradwell and Rainford 2015) yet crew–aircraft system effectiveness remains suboptimal. Quantifying in-flight WBV and SN dose enables fatigue prediction, supporting fitness-for-duty assessment and exposure-based rostering. This review introduces the helicopter noise and vibration exposure dose equations that can be used to identify the pilots' cumulative exposure that contributes to crews' fatigue. Multi-site measurement campaigns aligned with ISO 9612-2009 and ISO 1999-2013 are advocated to refine work methods and constrain cumulative exposure. Application to rostering is emphasized for duty periods exceeding 4 hours, which surpass the 5.5–6.3 h health-guidance band (Teixeira 2020) and approach the regulatory 8-hour ceiling that may itself potentiate fatigue by exceeding biomechanical tolerance limits.

BASE CONCEPTS

Whole-body vibration

Vibration denotes dynamic mass displacement and can be generated in a helicopter aircraft whether from powerplant imbalance, rotor aerodynamic forcing, or cabin structural response to rocking. Spectral decomposition—typically fast Fourier transform—extracts amplitude and frequency content across relevant bands. In rotorcraft, vibration diagnostics bifurcate into airworthiness monitoring (rotor track, drivetrain health, airframe fatigue life) and occupant comfort assessment; the latter remains underdeveloped regarding cumulative dose metrics for seated crew during extended offshore transits (Reddy *et al.* 2003; Pawar and Ganguli 2007; Diamanti and Soutis 2010; Martinez *et al.* 2015; dos Santos *et al.* 2016).

Beyond structural fatigue, vibration compromises crew and passenger wellbeing at specific frequencies, amplitudes, and cumulative doses. WBV refers to mechanical oscillation transmitted to a supported person via seat or floor interfaces. Pilots endure WBV across all flight phases; individual sensitivity varies with body mass, stature, age, contact area, and vibration direction. Exposure limits converge near 1.15 m/s^2 (ISO 1997). Transmissibility is frequency-dependent: below 12 Hz, energy propagates systemically, whereas above this threshold, effects localize. Impulsive noise events span ≤ 0.1 s; cabin ambient levels reach ~65 dB, with occupational 8-hour limits of 80–90 dB set by multiple agencies (Hostens and Ramon 2003).

Biodynamic research demonstrates tissue-specific resonance. Baig *et al.* (2014) identified peak lumbar–thoracic transmissibility at 2–4 Hz, invariant with vibration direction. Anh and Griffin (2007) report maximal discomfort perception at 3–13 Hz. Blackman (2019) quantified amplification factors by region: cervical and lumbar spine resonate at 4–5 Hz (transmissibility gain ~2.4× seat input); thoracic cavity at 5–6 Hz (~2.0×); cranial–shoulder coupling dominates 20–30 Hz (~3.5×).

These non-linear profiles explain region-specific discomfort patterns that do not scale linearly with floor measurements. Health and performance decrements manifest even at low oscillation amplitudes within these bands (ISO 1997).

ISO 2631 provides normative characterization of WBV without mandating a single analytical pathway. Its scope spans ground vehicles, marine craft, and industrial machinery domains predominated by shock-type, high-magnitude events (ISO 2018). Aviation applications involve sustained random vibration with lower peak amplitudes but longer durations, a regime which is absent from current annexes. No helicopter-specific measurement protocol exists under ISO 2631-1, and public exposure datasets are scarce, complicating threat assessment (Kåsin *et al.* 2011).

Directive 2002/44/EC retains interpretive ambiguities regarding measurement scale (*e.g.*, Richter *versus* Mercalli), equipment specification (accelerometer *versus* seismometer), and assessment frequency. Worker protection requires tripartite coordination—regulators, operators, and crew—with standards treated as minima rather than targets. A critical gap persists for in-flight and aquatic operations: observation protocols, assessor qualifications, and audit cadences remain undefined (Kåsin *et al.* 2011).

Tamer *et al.* (2021) proposed a generalized vibration index (GVI) that considers comfort, handling, visual effects, and foot-vibration concerns. Unlike traditional methods focusing on seat acceleration, GVI accounts for multiple contact points and sensory pathways, integrating ISO-based frequency weighting, ocular dynamics, and biodynamic models in a helicopter-pilot simulation. Its four subindices identify affected body regions at specific frequencies, aiding targeted vibration mitigation. Similarly, it is agreed that a seat-based index may significantly underestimate exposure, especially near the rotor's blade-passage frequency, in which visual and foot vibrations are more prominent. However, GVI is exploratory, challenging to implement operationally, and requires further validation across pilots, aircraft, and flight conditions. Its basis on a generic helicopter, vertical excitation, simplified pedal contact, and simulations limits its direct applicability.

Manufacturer datasheets offer supplementary reference data for noise and vibration levels but lack harmonization with occupational exposure metrics. Lifetime dose estimation from intermittent shock exposure presents methodological complexity. Current practice estimates daily and monthly forecasts from standardized exposure assumptions and annual duty hours, anchored to ISO 2631. Continuous monitoring and alternative instrumentation are recommended, with emphasis on deployable, non-disruptive tools accessible to non-specialists. This aligns with European Union's policy objectives to evaluate exposure reduction via evidence-based occupational health frameworks.

Therefore, all existing WBV standards and directives exclude aviation and maritime endorsement, demanding adapted or novel measurement methodologies with cross-sector applicability.

Sound-noise

Noise comprises unwanted, unpleasant, or communication-interfering acoustic energy. Human audition spans 20–20,000 Hz, with maximal sensitivity at 500–8,000 Hz—the band most susceptible to occupational impairment. Infrasound (< 20 Hz) lies below the perceptual threshold but may elicit mechanical responses in the vestibular and cochlear systems. Legal deafness is defined at 4,000 Hz (Alves-Pereira and Castelo Branco 2006).

Variation in SN sensitivity among individuals mirrors WBV. Impulsive noise thresholds peak at 120–140 dB for 0.1–0.25 s events. Occupational 8-hour limits range from 85–90 dB(A), with action levels above 80 dB in some jurisdictions such as Canada, the United States of America, and the European Union (CCOHS 1990; U.S. Department of Health and Human Services 1998; European Parliament 2003).

Helicopters generate noise mainly through mechanical and aerodynamic mechanisms. External noise, referenced to the cockpit and cabin, mainly comes from the top (main) and back (tail) rotors, including uniform, periodic, and random blade-mass effects, volume shift, and nonlinear aerodynamic effects at high-blade Mach numbers. The main rotor produces high-order harmonics and experiences random loads, while the tail rotor generates low-order harmonics and impulsive noise due to blade-vortex interactions at very high speeds (George 1978). Interior noise spectra superimpose discrete tones, harmonics, and broadband energy from avionics and environmental control systems, which alter the cockpit environment. Aerodynamic cockpit and cabin noise arises from both rotor flow fields, modulated by project geometry, inter-rotor aerodynamic interference, and angle-of-attack variations in cruise (*e.g.*, in offshore fleet types S-92, H175, AW139, AW169, AW189, H160). Fuselage–rotor–engine coupling and material impedance (composite *versus* metallic) further shape the acoustic field. Mechanical contributions originate in transmission shafts, auxiliary power unit (APU), gearboxes, drives shafts, and tail rotor drivelines, yielding airframe-specific signatures governed by rotor architecture and gear ratios (James 2005).

HEALTH IMPACTS OF WHOLE-BODY VIBRATION AND SOUND-NOISE IN ROTOR-WING CREWS

Tables 1 and 2 provide health effects on organs and body systems, as well as side effects on rotor-wing crews from exposure to vibration and noise.

WBV and HAV health effects have been catalogued for four decades (Tables 1 and 2). Chronic WBV exposure produces durable spinal pathology, with peak damage occurring at 10–12 Hz lumbar resonance (Harrer *et al.* 2005). Resultant low back pain (LBP) degrades physical conditioning and operational capability (Halmai *et al.* 2024).

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Table 1. Body systems affected by noise and vibration exposure*.

Body section	Systems or body organs affected in rotor-wing crews	Reference
Upper (neck to head)	Central nervous system	Pope *et al.* (1985); Dupuis and Zerlett (1987); Bongers *et al.* (1990)
Middle (waist to shoulder)	Cardiovascular, musculoskeletal, reproductive, urinary, nervous, endocrine, digestive and gastrointestinal, respiratory system	Lowson and Ollerhead (1969); Hawkes and Worsham (1970); Seidel *et al.* (1980); Gradwell and Rainford (2015)
Full body	Nervous, musculoskeletal and circulatory system	Lovesey (1979); Seidel *et al.* (1980); Gradwell and Rainford (2015)

*Rotor-wing crews are all members who are part of the flight operation/mission. In these cases, it depends on the type of flight activity. Those involved in Search-and-rescue (SAR) or helicopter emergency medical services (HEMS), activities who are not pilots but are part of the crew in the operation or mission are also affected.

Table 2. Resulting vibration and noise negative exposure effects and disorders on rotor-wing crews.

Related body section	Cause of whole-body vibration and sound-noise in rotor-wing crews	Reference
Upper (neck to head)	Depression, irritability, aggressiveness, difficulties with concentration, panic attacks and anxiety, vision distortion. Hearing momentary and permanent impairment (often reported), nervous breakdowns, stress-related symptoms; fatigue (reported when flying above 4 to 6 hours per day), loss of situation awareness	Lovesey (1979); Pope *et al.* (1985); Panjabi *et al.* (1986); Gradwell and Rainford (2015)
Middle (waist to shoulder)	Touch sensitivity; stiffness in the shoulders and back pain (most commonly reported); nutrient absorption reduction and decreased metabolism and sciatica pain; degenerative variations in the spinal, including lumbar inter-vertebral disc disorders; declines testosterone and estrogen production, dropping fertility and sexual appetite, menstrual deregulation, constipation, rises the risk of inflammatory bowel diseases (esophagitis, gastritis, colonitis, ileitis, and proctitis), cuts enzyme activity and diabetes; stomach ache or discomfort, nerve ulcers, gastric ulcers, irritable bowel syndrome, food allergies, stomach pains, reflux, nausea and weight oscillations; high insulin secretion that can lead to diabetes, harm to arteries and obesity; rise blood pressure, fast heart rate, higher risk of heart attack and stroke, rise harmful cholesterol; hormone fluctuations, calcium absorption, water retention, kidney stones, protein production, urinary tract infections	Lovesey (1979); Seidel *et al.* (1980); Pope *et al.* (1985); Panjabi *et al.* (1986); Dupuis and Zerlett (1987); Bongers *et al.* (1990); Cornelius *et al.* (1994); Gradwell and Rainford (2015)
Full body	Temperament swings, absence of energy, bones, joints (knees, elbows, lower back, neck) swelling, tension, diminished bone density, dormant muscle and cramps	Lovesey (1979); Seidel *et al.* (1980); Pope *et al.* (1985); Panjabi *et al.* (1986); Gradwell and Rainford (2015)

SN exposure produces sensorineural hearing loss, tinnitus, and vibroacoustic disease. Degradation of monaural and binaural signals compromises sound localization, self-motion perception, spatial direction, and auditory object identification, thereby delaying adaptive responses to environmental change. Central effects include memory impairment, attention deficit, headache, psychomotor slowing, fatigue, stress, anxiety, and degraded decision latency (Kuronen *et al.* 2004; McReynolds 2005; Alves-Pereira and Castelo Branco 2006; En–tong *et al.* 2008; Reinhart 2008; Gradwell and Rainford 2015). Combined WBV and SN exposure generates musculoskeletal pathology concentrated in the cervical and lumbar spine, with secondary intellectual and performing degradation. Tension potentiates exhaustion and psychomotor slowing. The net effect is bidirectional impairment of somatic and psychological health (Sirevaag *et al.* 1993; Kato *et al.* 2009; Sneddon *et al.* 2013; Gradwell and Rainford 2015).

Whole-body vibration in-flight health impacts

Helicopter pilots develop musculoskeletal and neurological sequelae from WBV, such as lumbar muscle irritation, inflammation, and dull or aching LBP involving the Z-axis (flexion, extension, rotation). Pathology spans disc herniation, tendinopathy, ligamentous strain, and neural compression. Aetiology includes microtrauma, tissue failure, metabolic and microvascular insult, plus degenerative change—modulated by age, stature, body mass, and seated posture. Fatigue-driven neurocognitive decrement degrades situational

awareness, attention, vigilance, and psychomotor control, elevating accident risk. Cognitive fatigue further impairs decision-making and amplifies anxiety (Hubbard *et al.* 1971; Griffin 1977; Auffret *et al.* 1980; Seidel *et al.* 1980; Pope *et al.* 1985; Pope *et al.* 1987; Panjabi *et al.* 1986; Dupuis and Zerlett 1987; Boshuizen *et al.* 1989; Bongers *et al.* 1990; Bovenzi 1996; Ladner 1997; De Oliveira *et al.* 2001; Fletcher and Dawson 2001; Kittusamy and Buchholz 2004; Mansfield 2004; Ahn and Griffin 2007; Cunningham *et al.* 2010; Kåsin *et al.* 2011; Gaydos 2012; Baig *et al.* 2014; Gradwell and Rainford 2015; McMahon and Newman 2018; Ballard *et al.* 2020).

Empirical reports document onset of leg and back pain at 2–4 hours into flight, with symptom escalation over such duration. Post-flight recovery extends to several hours; in some cases, pain persists 24–48 hours post-landing (Harrer *et al.* 2005). Safety-margin analysis identified below 7 hours as the threshold where risk accelerates (Teixeira 2020). Despite accumulating evidence, regulatory bodies have not revised exposure limits.

The AW189 airframe is employed to illustrate WBV–health relationships. Figure 1a depicts the seat and pilot monitoring body position. Figures 1b and 1c mark triaxial accelerometer positions per ISO 2631-1 (ISO 1997): seat cushion, backrest, and floor interface. Figure 1c additionally maps discomfort loci and mechanical compression points.

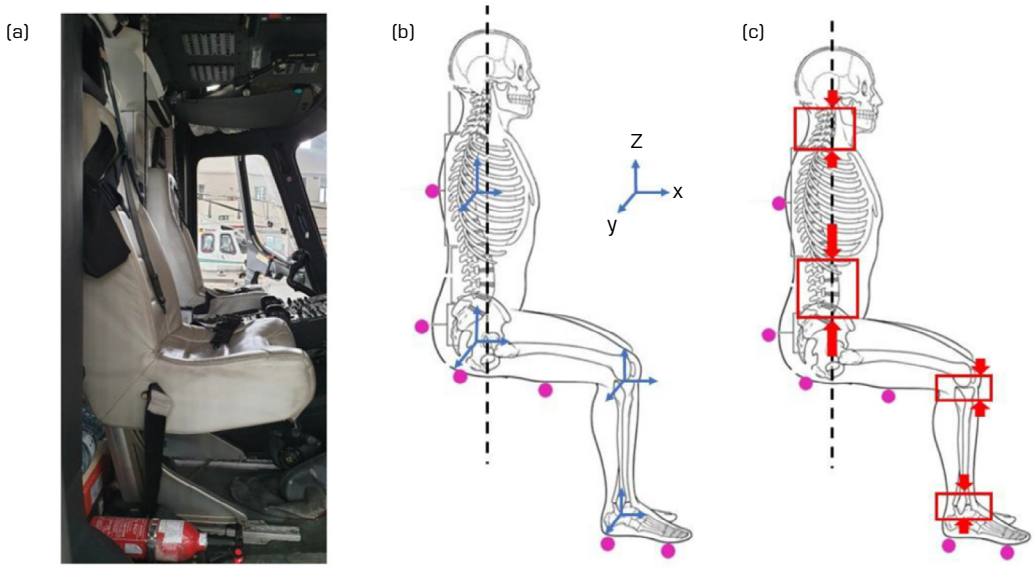

Figure 1. (a) Position while pilot monitoring and contact points on an AW189 seat; (b) body interaction point (pink); and (c) flight crew discomfort and compression points.

Figure 2 contrasts normal and flight-induced postures; it depicts the pilot's flying position: left hand on the collective lever, right hand on the cyclic stick, feet on the anti-torque pedals. The flying position induces posterior pelvic tilt, sacral and coccygeal rotation, and elevated intradiscal pressure at L1–L3 (Panjabi *et al.* 1986). Harrer *et al.* (2005) documented that at ~4 hours into a 7-hour mission, pilots reported severe LBP, paresthesia, and impaired egress from circulatory compromise. Nocturnal pain persisted post-flight. Inadequate seat cushioning compressed the sciatic nerve; absent lumbar support produced paraspinal muscle fatigue.

Figure 3 illustrates the monitoring position: prolonged seated posture flattens lumbar lordosis via posterior pelvic tilt, redistributing lumbopelvic load abnormally.

Figure 4 shows the pilot flying position with controls engaged. Anthropometric variation—particularly limb length—modulates comfort; taller pilots may tolerate the posture better. Limited seat and pedal adjustability amplify inter-individual variation in discomfort.

European Union's Directive 2002/44/EC acknowledges workspace design without prescribing standards for position assessment; ISO 2631-1 (ISO 1997) similarly omits seated posture norms. Zadoń *et al.* (2021) quantified pelvic kinematics: standing anteversion ranged from -11° to -21° (greater in females); seated retroposture was present in > 70% of subjects, with < 30% maintaining anteversion. Seated pelvic displacement ranged from 13.5° to 28.7°, elevating lumbar joint loads by > 150% relative to standing. Trunk flexion and pelvic retroposition were primary load amplifiers.

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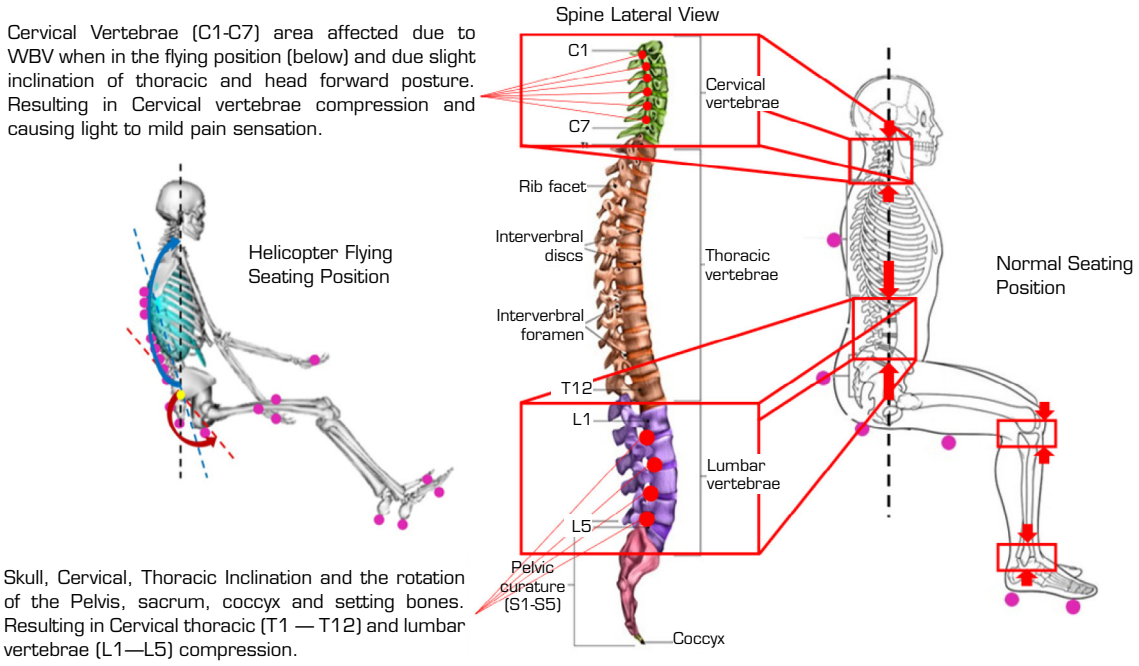

Figure 2. Flight crew member, body posture and contact points.

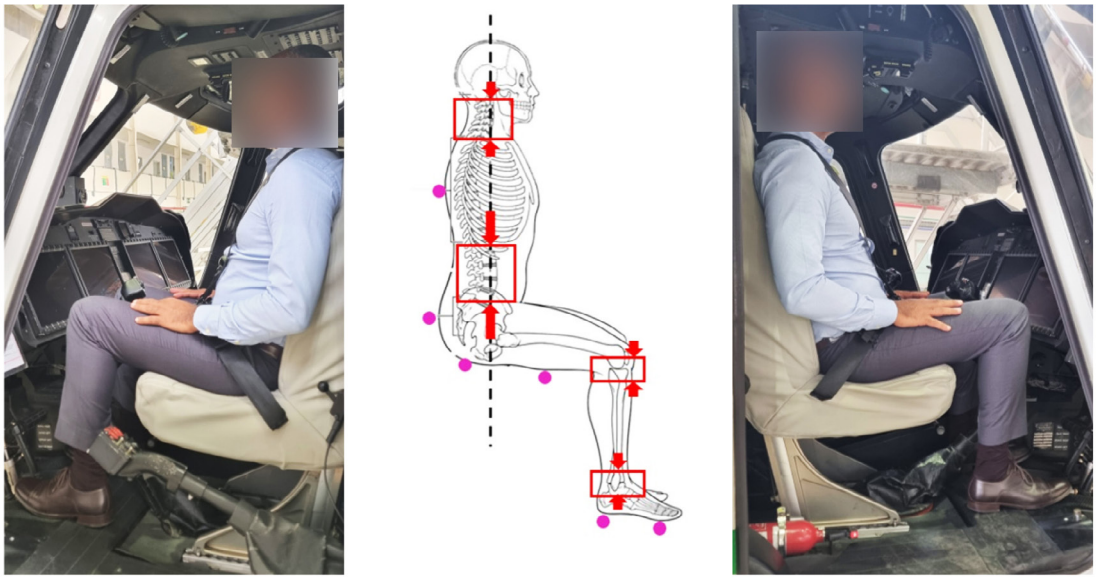

Figure 3. Pilot monitoring: flight crew position without flight controls, body contact, and vibration points.

Sound-noise in-flight exposure

Rotorcraft acoustic spectra span 90–1,000 Hz (George 1978; Pope *et al.* 1985; Teixeira 2020). The critical band is infrasound (1–20 Hz) that can cause oscillations in the tympanic membrane, ossicular chain, and semicircular canal, potentially affecting cochlear and vestibular functions (Teixeira 2020).

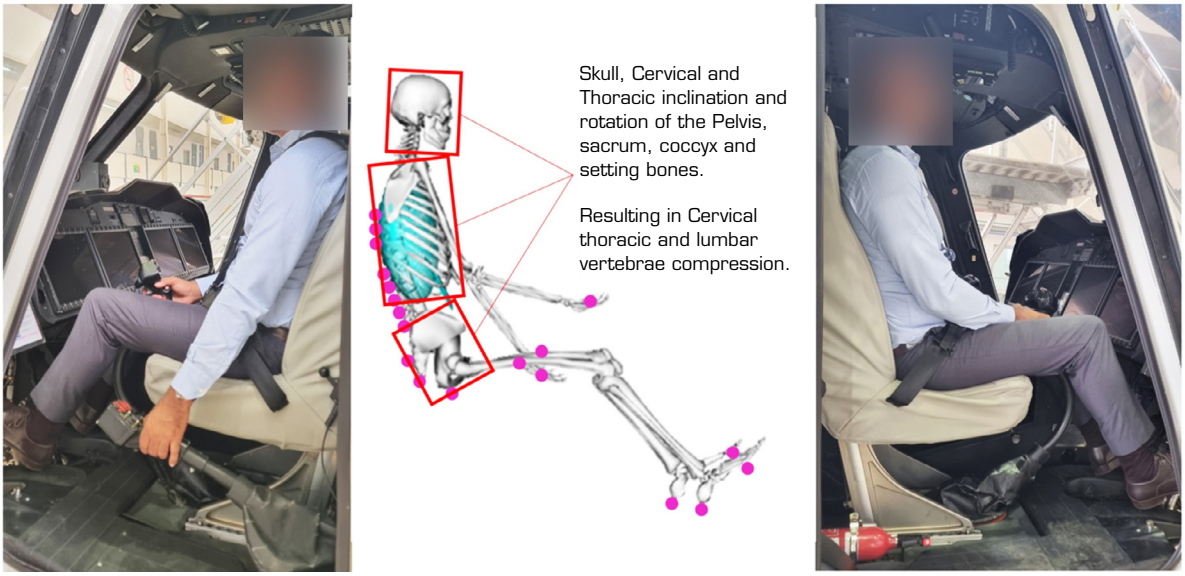

Figure 4. Pilot flying: flight crew position with flight controls, body contact, and vibration points.

Non-occupational auditory risk behaviors, recreational noise, high-output earphones, the absence of hearing protection in noisy environments, and mechanical canal trauma compound occupational exposure, accelerating fatigue and related hearing injury.

Hearing protection attenuation varies by device class. Active noise reduction (ANR) headsets achieve ~15 dB reduction below 800 Hz at < 135 dB sound pressure level, with degraded performance above this threshold (Mckinley *et al.* n.d.). In the Mckinley *et al.* (n.d.) study, two noise measurement methods were employed: passive protection (deep-insert or custom-moulded earplugs) and active ANR configurations were compared; combined use remains rare in any commercial operations. The dominant helicopter noise band is 0–500 Hz, with residual energy above 500 Hz. In a Cessna 172 cruise, cockpit levels reached ~95 dB; ANR-equipped aviation headsets delivered 19–25 dB attenuation, confirming low-frequency efficacy (Burgess and Molesworth 2016). Conventional earmuffs and earplugs provide 10–30 dB frequency-dependent attenuation (Kuronen *et al.* 2004). Laboratory certification employs crew helmets and earmuffs; helmets are standard in the armed forces and search-and-rescue (SAR) missions and are generally used for helicopter emergency medical services (HEMS), but are absent from offshore oil and gas helicopter operations.

Standard headphones attenuate ≤ 9 dB below 300 Hz and ≤ 12 dB above 300 Hz; literature reports 15–30 dB for optimized devices (George 1978; Fitzpatrick 1988; King *et al.* 1996; United States 2004). Kuronen *et al.* (2004) measured cabin noise at ~100 dB, ~10 dB above ear-level exposure, with helmets providing superior cranial coverage and spectral attenuation relative to headphones. Early-career pilots accumulate hours rapidly, then decelerate; this temporal pattern may obscure cumulative risk perception. The author's knowledge emphazises that helmets provide pilots with better head protection and reduce surrounding sound absorption more than headphones during daily use.

The above-referred regulations and standards, such as Canadian Center for Occupational Health and Safety (CCOHS), National Institute for Occupational Safety and Health (NIOSH), ISO 1999-2013, and Directive 2003/10/EC, contain unresolved uncertainties. None prescribe evaluation criteria, combined-source assessment protocols for infrasound and low-frequency noise, or equipment specifications (Alves-Pereira and Castelo Branco 2006). Maritime and aviation applications remain particularly underspecified. Environmental modifiers—temperature, humidity, pressure, and altitude-dependent sound speed [*e.g.*, 304 m (1,000 ft) *versus* 1,524 m (5,000 ft) during helicopter flights]—introduce measurement variability absent from ground-based protocols.

Current noise standards fail for air and maritime domains, requiring alternative strategies. The proposed methodology delivers a rapid, validated, non-specialist daily assessment of combined SN and WBV exposure, generating actionable safety data without expertise barriers.

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Vibration (ISO 2631; Directive 2002/44/EC) and noise (ISO 1999-2013; European Parliament 2003) lack aviation and maritime applicability, featuring ambiguous protocols, unsafe in-flight measurement guidance, and non-harmonized equipment specifications. Combined standards omit frequency-weighted root mean square acceleration for infrasound and low-frequency noise, expressed as 8 hours equivalent continuous dB; and environmental correction factors (humidity, altitude, pressure).

Unclear compliance methods or equipment guidelines leave workers vulnerable because the action value exceeds 0.5 m/s^2 (8-hour energy ambiguous compliance pathways expose workers: the 0.5 m/s^2 action value [vibration dose value (VDV) basis] permits 8-hour cumulative doses entering the ISO 2631-1 health guidance zone (VDV > 9 m/s^2), exceeding Occupational Safety and Health Administration (OSHA), ISO 1999-2013, and Directive 2003/10/EC thresholds at 85 dB(A) time-weighted average.

An innovative real-time assessment method enables non-expert workers to evaluate combined SN and WBV exposure cost-effectively, aligned with ISO 2631 and European Union's directives. The approach prioritizes preventive cumulative monitoring, immediate safety status determination, and regulatory gap closure through validated, accessible data collection.

Piňosová *et al.* (2018) constructed a noise-induced hearing impairment risk matrix: exposure > 95 dB scored probability 5 (near-certain occurrence) and severity 5 (catastrophic, progressive illness). This framework is referenced in Table 3.

Table 3. Progression of noise illnesses and health impact.

Phases of illness and impacts on health	Source
Phase 1 illness includes fatigue, stress, concentration problems, decreased cognition, reflex muscle strain, tinnitus, and mild speech issues. Phase 2 adds symptoms like temporary hearing loss, circulatory problems, heart issues, and communication difficulties. By Phase 3, symptoms progress to hearing loss, deafness, and severe sleep issues.	Piňosová *et al.* (2018)
Phase 1 illness causes minor mood swings, indigestion, heartburn, mouth or throat infections, and bronchitis. Phase 2 adds chest pain, major mood swings, back pain, fatigue, skin infections, stomach inflammation, urinary pain and blood, conjunctivitis, allergies. Phase 3 includes all prior symptoms plus psychiatric issues, nasal, digestive, and conjunctival hemorrhages, varicose veins, hemorrhoids, ulcers, colitis, vision issues, headaches, severe joint pain, and neurological problems.	(Alves-Pereira and Castelo Branco 2006)

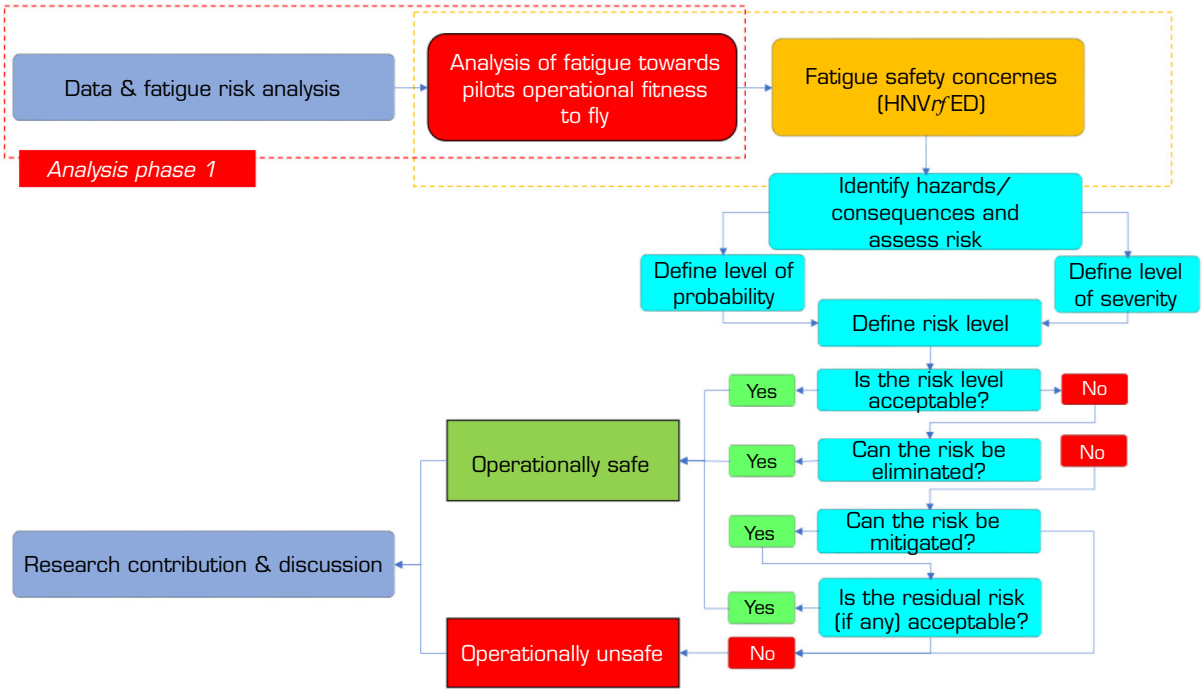
Corroborating studies confirm chronic noise morbidity (Stave 1973; Fitzpatrick 1988; Kuronen *et al.* 2004; James 2005; Jaruchinda *et al.* 2005; McReynolds 2005; En–tong *et al.* 2008). Hearing loss progresses through cumulative degeneration of sensory cells.

The 8-hour regulatory limit exceeds the 6.3-hour health-guidance threshold, prioritizing administrative compliance over worker protection. Rotorcraft-specific hazards—WBV and SN—remain excluded from cockpit risk regulations. Absent a real-time combined exposure index, operational authorization will perpetuate approved doses capable of inducing permanent spinal and auditory pathology.

WHOLE-BODY VIBRATION AND SOUND-NOISE CHARACTERIZATION METHODS

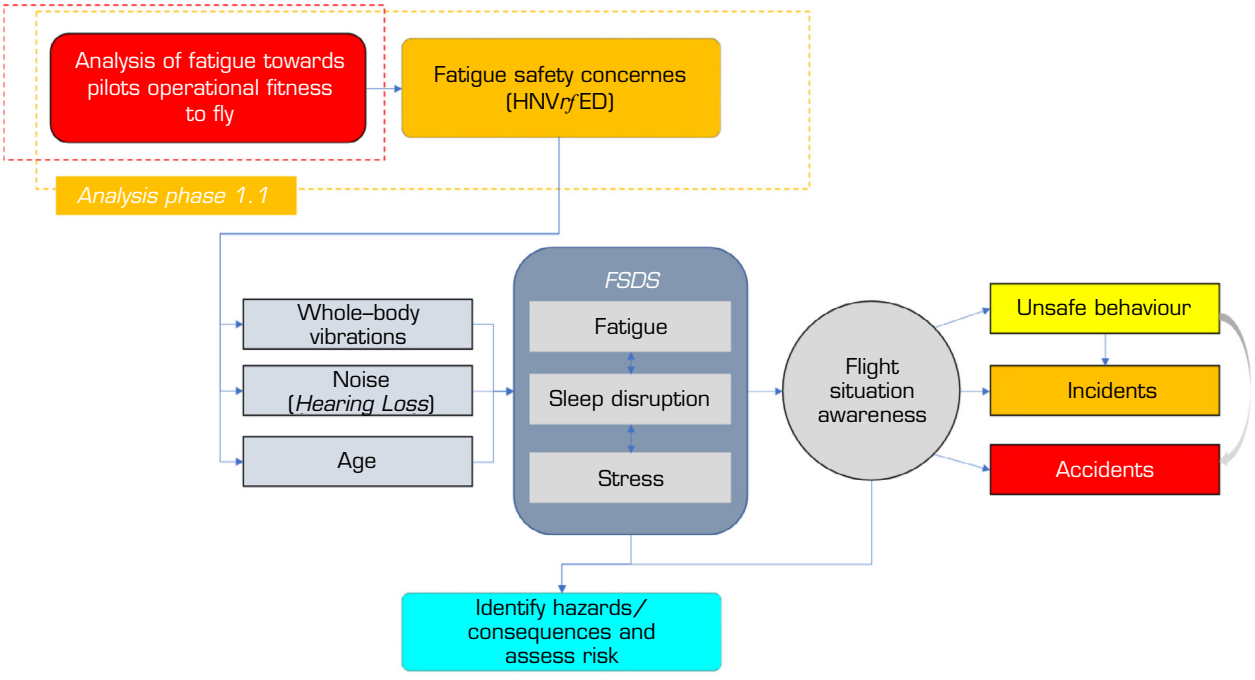
Optimal characterization employs microphones and triaxial accelerometers for in-field acquisition of SN and WBV. This section reviews the baseline methodology, equipment specifications, and health correlations, exemplified in the AW139 and AW189 offshore fleets. Figures 5 and 6 present the integrated WBV/SNV characterization and rostering methodology. The framework adapts ICAO Doc 9859 safety management systems (SMS) hazard identification, incorporating risk mitigation, hierarchy-of-controls categorization, and author-modified contextual parameters (ICAO 2018).

Figure 5 depicts the workflow: post-acquisition, HNVrfED (real-flight dose) calculation determines fitness-for-duty. Figure 6 details fatigue-derived safety concerns. Hazard severity and likelihood are evaluated via binary (yes/no) decision gates to establish operational safety status. Fatigue, sleep disruption, stress, and situational awareness are classified into high/low categories per Teixeira's study (2020).



Source: Adapted from Teixeira (2020).

Figure 5. Study of fatigue related to operational readiness.



Source: Adapted from Teixeira (2020).

Figure 6. Analyses of fatigue safety concerns.

Sound and vibration data acquisition equipments

Equipment selection criteria:

- Vibration—triaxial (x, y, z) recording in dB and m/s^2, portable, lightweight, capturing roll (φ), pitch (θ), and yaw (ψ);
- Sound—audio class 1 certified, dB and m/s^2 output, portable, lightweight, with accessible data retrieval.

ISO 2631-1 (ISO 1997) provides WBV assessment. Multi-site (seat pan, backrest) and multi-axis measurements receive frequency- and direction-dependent weightings according to assessment objective: health, comfort, perception, or motion sickness. Weighting variation reflects non-uniform biodynamic transmissibility.

Triaxial micro-electro-mechanical systems (MEMS) accelerometers are prevalent in biomedical and tremor research (Wannenburg and Malekian 2017). Sensors resolve x, y, z acceleration into roll (φ), pitch (θ), and yaw (ψ) (Fig. 1b) (Pei *et al.* 2010; Wannenburg and Malekian 2017; Majumder and Deen 2019; Andersson *et al.* 2024).

Seat-pad accelerometry quantifies ischial tuberosity interface dynamics, yet disk-pad deployment on commercial services raises safety objections. Military or dedicated research flights accommodate such instrumentation, but cost and operational impracticality limit fleet-wide fatigue risk management system (FRMS) data acquisition. Figure 7 depicts a triaxial MEMS seat-pad accelerometer (Castle KD1009) positioned at the cushion–occupant interface.

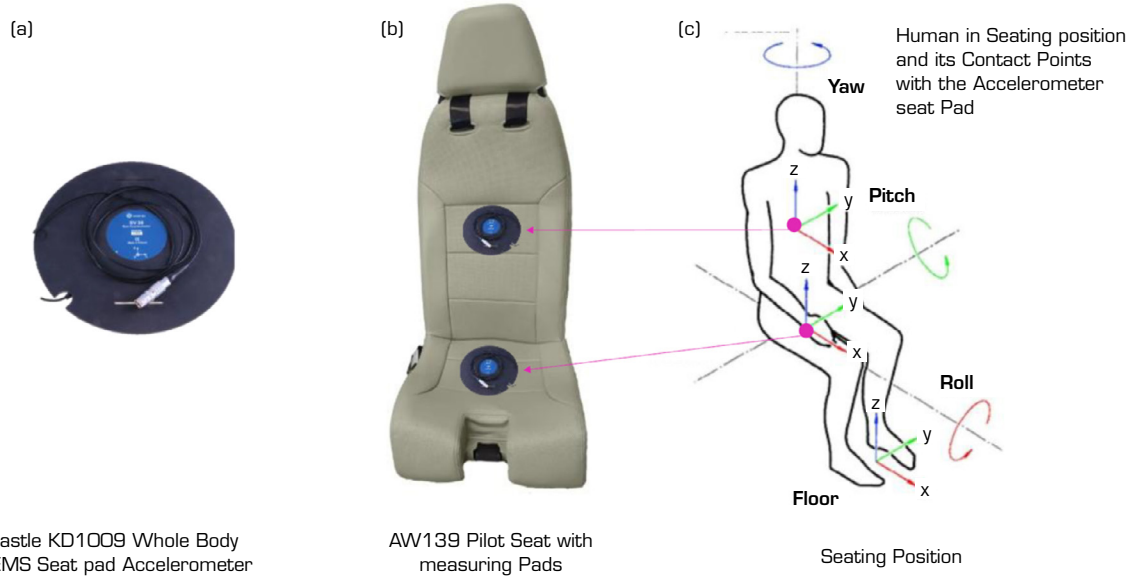


Figure 7. Seat pad accelerometer for whole-body vibration (Castle KD1009). (a) Device detail; (b) AW139 seat placement; (c) body contact points and axis orientation.

Blackman (2019) reported that 89% of the analyzed flight events exceeded American Conference of Governmental Industrial Hygienist (ACGIH) action levels, with > 20% exceeding threshold limits. All 18 trials surpassed the ISO 2631-1 vibration dose action value; > 20% exceeded the exposure limit.

Seat-pan measurement per ISO 2631-1 may underestimate actual pilot exposure, as biodynamic coupling varies with foot position (floor rest *versus* pedal contact) and control engagement. Calf transmissibility is floor-contact dependent; arm transmissibility increases with cyclic/collective manipulation. Full-body pad instrumentation is precluded on commercial flights by safety, vibration-damping, and acoustic-attenuation concerns.

Military validation employed comparable pads on MH-60S and UH-60L platforms. MH-60 Sea Hawk and UH-60L Black Hawk helicopter platforms shown in Fig. 7, Harrer et al. (2005) documented 6–8-hour missions with WBV-induced leg and back pain at 2–4 hours, situational awareness degradation from postural shifting, and 6-hour cushion effectiveness before limit

exceedance. Smith (2019) identified high-frequency spinal loading mechanisms distinct from low-frequency regimes, with significant in-flight pain impact suggesting standard underestimation of military rotorcraft risk and necessitating protocol revision. Both studies address WBV in isolation, omitting SN as independent fatigue variables. An integrated WBV–SN metric is required, with predefined outcome variables. The here proposed strategy quantifies combined exposure, classifies fatigue by accumulated dose, and discriminates stationary (monitoring) from active (flying) postures via triaxial accelerometry across flight phases.

Numerical analyses from ISO equations

Equations 1 and 1.1 relate to vibration daily exposure serves as the comparator against directive action and limit values. For multi-period workdays, energy-equivalent magnitude is computed per axis via ISO 2631-1.

$$A_{1(8)} = k_l \sqrt{\frac{1}{T_0} \sum_i a_{wli}^2 T_i} \tag{1}$$

where $A_{1(8)}$: daily exposure (m/s^2), axis l ∈ {x, y, z}; $K_x = K_y = 1.4$, Kz = 1 (directional weightings); $T_0 = 28{,}800$ s (8-hour reference); a_{wli}^2: frequency-weighted root mean square acceleration over interval T_i.

Axis orientation is shown in Fig. 7. WBV dosage employs the vibration dose value (VDV), defined as Eq. 1.1:

$$VDV = \sqrt[4]{\int_0^T [a_w(t)]^4 dt} \tag{1.1}$$

where $a_w(t)$: weighted instantaneous acceleration; T: exposure duration; VDV in m/s^1.75.

Action level: 0.5 m/s^2 root mean square or 9.1 m/s^1.75 VDV. Exposure limit: 1.15 m/s^2 root mean square or 21 m/s^1.75 VDV.

Equation 2 is the noise daily exposure L_EX,8h (dB), defined in ISO 9612-2009 and ISO 1999-2013 as the A-weighted level normalized to an 8-hour nominal workday:

$$L_{EX,8h} = L_{pAeq,Te} + 10 \times \log (T_e / T_0)\ \text{dB} \tag{2}$$

where T_e: effective working day (h); $L_{pAeq,Te}$: A-weighted equivalent continuous level for T_e; T_0: 8-hour reference.

For n-day averaging (*e.g.*, weekly normalization to 8-hour equivalent) (Eq. 3):

$$L_{EX,8h} = 10 \times \log \left[\frac{1}{c} \sum_{i=1}^{n} 10^{0,1(L_{EX,8h})i} \right]\ \text{dB} \tag{3}$$

where c: n for simple averaging, or fixed (*e.g.*, $c = 5$ for seven-day normalization to five workdays).

Irregular exposure treatment per ISO 9612 (ISO 2009; 2013).

Alternative method for multiple sources: vibration and acoustic

Equations 4 and 5 define the helicopter noise and vibration estimated exposure dose (HNVED), adapted from multi-source acoustic summation in decibels. Equation 6 incorporates manufacturer data and ISO 2631-5 (ISO 2018) parameters:

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$$HNVED = (dB_{total}) * TFT \tag{4}$$

$$HNVED = \left[10 * LOG\left(10^{\left(\frac{manfAvgND(dB1)}{10}\right)} + 10^{\left(\frac{manfAvgVD(dB2)}{10}\right)}\right)\right] * TFT \tag{5}$$

A correction distinguishes estimated based on manufacture data from measured flight data. Equations 6–8 modify the decomposition of Eqs. 4 and 5 for real-flight application:

$$HNVmfED = \left[10 * LOG\left(10^{\left(\frac{manfAvgND(dB1)}{10}\right)} + 10^{\left(\frac{manfAvgVD(dB2)}{10}\right)}\right)\right] * TFT \tag{6}$$

$$HNVrfED = (dB_{total}) * TFT \tag{7}$$

$$HNVrfED = \left[10 * LOG\left(10^{\left(\frac{Real\ Flight\ AvgND(dB1)}{10}\right)} + 10^{\left(\frac{Real\ Flight\ AvgVD(dB2)}{10}\right)}\right)\right] * TFT \tag{8}$$

where HNVED: estimated dose; HNVrfED: real-flight dose; HNVmfED: manufacturer-data dose; RealFlightAvgND(dB1): 30-s cruise noise average (app-measured, not peak); RealFlightAvgVD(dB2): 30-s cruise vibration average (magnitude/acceleration, dB-converted); TFT: total flight time (decimal hours).

HNVrfED is restricted to cruise phase; take-off and landing are excluded because they demand undivided crew attention and exhibit manufacturer-documented vibration and noise maxima that would confound routine exposure assessment. The decimal-hour formulation prevents inflation due to second-scale multiplication (28,800 s = 8 h).

Equations 9 and 10 convert Richter-scale magnitude to decibels and re-expressed them in real flight average vibration dose:

$$\mathbf{dB} = \mathbf{20} \times \log_{\mathbf{10}}(A) \tag{9}$$

$$RealFlightAvgVD = \mathbf{20} \times \log_{\mathbf{10}}(A) \tag{10}$$

where A: mean seismic-wave amplitude from ≥ 30-s vibrometer recording.

CONCLUSION

Manufacturer specifications and field methodology confirmed that routine helicopter operations expose pilots to cumulative SN and WBV doses exceeding occupational health standards. This requires operation-specific daily limits and ceiling thresholds. The HNVrfED framework supports task-calibrated duty–rest scheduling and FRMS trend detection, thereby maintaining SMS continuity and enhancing safety performance.

Results are operationally pertinent to rotor-wing crews. In-field measurements exceed ISO 2631-2018 WBV and ISO 1999-2013 SN limits across all flight phases—take-off, climb, cruise, approach, and landing—relative to manufacturer-declared values.

To the author's knowledge, no published combined WBV–SN limits for rotorcraft or multi-source environments exist. Synergistic exposure intensifies muscular fatigue and systemic morbidity, requiring protective rest intervals in roster design. External performance modifiers (circadian phase, sleep debt, nutrition) remain outside this scope.

Future research prospects

Publicly accessible seat-level WBV and SN datasets for pilots remain scarce. This review identified priority research axes: fatigue aetiology, WBV/SN dose–response, and inter-individual trait modulation (age, sex, anthropometry). Prospective in-flight studies with healthy pilots across demographic strata, conducted over one–three-month observation windows, are required to establish causal pathways for fatigue, performance decrement, and erosion of situational awareness.

Specific recommendations:

- Potential offshore in-flight WBV/SN/fatigue characterization;
- Dose-limit determination for 21, 28, and 35 day rotation schemes;
- Exposure-minimization strategies to define optimal daily flight time ceilings.

Providing detailed facts helps this occupational group better understand helicopter pilots' fatigue, fitness, and health issues. This improved awareness enables more precise conclusions.

Key points

- First combined analysis of infrasound, low-frequency noise, and WBV in offshore rotor-wing crews; daily doses exceed ISO 2631-5 (ISO 2018), ISO 1999-2013, and Directives 2002/44/EC, 2003/10/EC thresholds;
- Novel HNVrfED equations enable portable, in-flight combined exposure quantification;
- Decibel-based multi-source aggregation method introduced;
- Deliverables: safety risk analysis matrix and operational risk condition chart for FRMS integration;
- Eight-hour regulatory limits exceed health-guidance WBV doses; exposure-optimized work–rest scheduling required;
- FRMS and SMS applications for 21/28/35-day offshore rotations; non-specialist operability;
- Regulatory vacuum: no combined WBV–SN standards for aviation/maritime; ISO 2631-1 and Directive 2002/44/EC omit in-flight protocols; noise standards ignore altitude, humidity, and pressure corrections.

CONFLICT OF INTEREST

The author is employed as an active line pilot by the helicopter operator that authorized access to the AW189 and AW139 for data collection. This professional affiliation provided the necessary operational environment for the study. However, the employer had no role in the study design, data analysis, interpretation of the noise and vibration metrics, drafting of the manuscript, or the decision to publish. The research was conducted independently, and the author declares no competing financial or personal interests.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable.

AUTHORS' CONTRIBUTION

Conceptualization: Teixeira C.L.D.; **Formal Analysis:** Teixeira C.L.D.; **Investigation:** Teixeira C.L.D.; **Resources:** Teixeira C.L.D.; **Supervision:** Freitas M.J.M., Costa P.F.R. **Validation:** Teixeira C.L.D.; **Data curation:** Teixeira C.L.D.; **Writing – original draft:** Teixeira C.L.D.; **Writing – review and editing:** Costa P.F.R.; **Final approval:** Teixeira C.L.D.

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DECLARATION OF USE OF ARTIFICIAL INTELLIGENCE TOOLS

During the preparation of this work, the author utilized artificial intelligence (AI) tools solely to enhance conceptual understanding of publishing protocols and to rephrase, structure, and refine the language of the final manuscript's disclosure sections for academic clarity. No AI tools were used to generate, alter, or analyze the research data, flight metrics, or scientific conclusions. The author reviewed and edited all tool-assisted outputs and takes full responsibility for the accuracy, originality, and overall content of this publication.

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REFERENCES

Ahn SJ, Griffin MJ (2007) Effects of frequency, magnitude, damping, and direction on the discomfort of vertical whole-body mechanical shocks. J Sound Vib 311(1-2):485-97. https://doi.org/10.1016/j.jsv.2007.09.026

Alves-Pereira M, Castelo Branco NAA (2006) Vibroacoustic disease: Biological effects of infrasound and low-frequency noise explained by mechanotransduction cellular signalling. Prog Biophys Mol Biol 93(1-3):256-79. https://doi.org/10.1016/j.pbiomolbio.2006.07.011

Andersson R, Bermejo-García J, Agujetas R, Cronhjort M, Chilo J (2024) Smartphone IMU sensors for human identification through hip joint angle analysis. Sensors 24(15):4769. https://doi.org/10.3390/s24154769

Auffret R, Delehaye RP, Merges PJ (1980) Vertebral pain in helicopter pilots. NASA Technical Reports Server. Available at: https://ntrs.nasa.gov/citations/19800019542

Baig HA, Dorman DB, Bulka BA, Shivers BL, Chancey VC, Winkelstein BA (2014) Characterization of the frequency and muscle responses of the lumbar and thoracic spines of seated volunteers during sinusoidal whole body vibration. J Biomech Eng 136(10):101002. https://doi.org/10.1115/1.4027998

Ballard MT, Madison AM, Chancey VC (2020) Human response effects to whole-body vibration in aviation: a brief review. Available at: https://apps.dtic.mil/sti/tr/pdf/AD1098433.pdf

Blackman CG (2019). Whole body vibration of military aircrews on mh-60 seahawk helicopters: risk assessment in relation to lower back pain. University of California. Available at: https://www.researchgate.net/publication/228976687_Whole_Body_Vibration_Exposure_for_MH-60S_Pilots

Bongers PM, Hulshof CTJ, Dljkstra L, Boshuizen HC, Groenhout HJM, Valken E (1990) Back pain and exposure to whole body vibration in helicopter pilots. Ergonomics 33(8):1007-26. https://doi.org/10.1080/00140139008925309

Boshuizen HC, Bongers PM, Hulshof CTJ (1989) Back disorders and occupational exposure to whole-body vibration. Int J Ind Ergon 6(1):55-9. https://doi.org/10.1016/0169-8141(90)90050-C

Bovenzi M (1996) Low back pain disorders and exposure to whole-body vibration in the workplace. Semin Perinatol 20(1): 38-53. https://doi.org/10.1016/S0146-0005(96)80056-5

Burgess M, Molesworth BRC (2016) The noise reduction provided by aviation headsets. Acoustics Australia 44(1):95-9. https://doi.org/10.1007/s40857-016-0050-y

Canadian Center for Occupational Health and Safety (CCOHS) (1990) Noise-occupational exposure limits in Canada. Canada: CCOHS. Available at: https://www.ccohs.ca/oshanswers/phys_agents/noise/exposure_can.pdf

Cornelius KM, Redfern MS, Steiner LJ (1994) Industrial ergonomics postural stability after whole-body vibration exposure. Int J Ind Ergon 13(4):343-51. https://doi.org/https://doi.org/10.1016/0169-8141(94)90091-4

Cunningham LK, Docherty S, Tyler AW (2010) Prevalence of low back pain (LBP) in rotary wing aviation pilots. Aviat Space Environ Med 81(8):774-8. https://doi.org/10.3357/ASEM.2736.2010

De Oliveira CG, Simpson DM, Nadal J (2001) Lumbar back muscle activity of helicopter pilots and whole-body vibration. J Biomechanics 34(10):1309-15. https://doi.org/10.1016/S0021-9290(01)00090-2

Diamanti K, Soutis C (2010) Structural health monitoring techniques for aircraft composite structures. Prog Aerosp Sci 46(8):342-52. https://doi.org/10.1016/j.paerosci.2010.05.001

Dupuis H, Zerlett G (1987) Whole-body vibration and disorders of the spine. International Arch Int Arch Occup Environ Health 59:323-36. https://doi.org/10.1007/BF00405276

En–tong W, Wei–xi G, Wei C, Xiao–li M, Hui X, Jun C (2008) Detection of early noise–induced hearing impairment in pilots. J Otology 3(2):108-12. https://doi.org/10.1016/S1672-2930(08)50023-7

European Parliament (2002) Directive 2002/44/EC. Minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration). Official J Eur Union. Available at: https://eur-lex.europa.eu/resource.html?uri=cellar:546a09c0-3ad1-4c07-bcd5-9c3dae6b1668.0004.02/DOC_1&format=PDF

European Parliament (2003) Directive 2003/10/EC of the European Parliament and of the Council of 6 February 2003 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise). Official J Eur Union. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32003L0010

Fitzpatrick DT (1988) An analysis of noise-induced hearing loss in army helicopter pilots. Aviat Space Environ Med 59(10):937-41.

Fletcher A, Dawson D (2001) Field-based validations of a work-related fatigue model based on hours of work. Transp Res F: Traffic Psychol Behav 4(1):75-88. https://doi.org/10.1016/S1369-8478(01)00015-8

Gaydos SJ (2012) Low back pain: Considerations for rotary-wing aircrew. Aviat Space Environ Med 83(9):879-89. https://doi.org/10.3357/ASEM.3274.2012

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George AR (1978) Helicopter noise: State-of-the-art. J Aircraft 15(11):707-15. https://doi.org/10.2514/3.58436

Gradwell DP, Rainford DJ (2015) Ernsting's Aviation and Space Medicine. 5th ed. C. Press.

Griffin MJ (1977) The evaluation of human exposure to helicopter vibration. Aeronaut J 81(795):110-23. https://doi.org/10.1017/S0001924000032498

Halmai B, Holsgrove TP, Vine SJ, Harris DJ, Williams GKR (2024) The after-effects of occupational whole-body vibration on human cognitive, visual, and motor function: A systematic review. Appl Ergon 118:104264. https://doi.org/10.1016/j.apergo.2024.104264

Harrer KL, Yniguez D, Majar M, Ellenbecker D, Estrada N, Geiger M (2005) Whole body vibration exposure for MH-60S pilots. Available at: https://www.researchgate.net/publication/228976687_Whole_Body_Vibration_Exposure_for_MH-60S_Pilots/link/5405cff70cf2c48563b1b824/download?_tp=eyJjb250ZXh0Ijp7ImZpcnN0UGFnZSI6InB1YmxpY2F0aW9uIiwicGFnZSI6InB1YmxpY2F0aW9uIn19

Hawkes GR, Worsham RW (1970) Time perception for helicopter vibration and noise patterns. J Psychol 76(1):71-7. https://doi.org/10.1080/00223980.1970.9916822

Hostens I, Ramon H (2003) Descriptive analysis of combine cabin vibrations and their effect on the human body. J Sound Vib 266(3):453-64. https://doi.org/10.1016/S0022-460X(03)00578-9

Hubbard HH, Lansing DL, Runyan HL (1971) A review of rotating blade noise technology. J Sound Vib 19(3):227-49. https://doi.org/10.1016/0022-460X(71)90686-9

International Civil Aviation Organization (ICAO) (2018) Doc 9859: Safety Management Manual. 4th ed. ICAO. Available at: https://omnisms.aero/wp-content/uploads/2019/08/ICAO-Doc-9859-SMM_Edition-4.pdf

International Organization for Standardization (ISO) (1997) ISO-2631-1: Mechanical vibration and shock: evaluation of human exposure to whole-body vibration Part 1. Available at: https://standards.iteh.ai/catalog/standards/sist/ca86d99a-070f-4d3e-a379-a4aa31d09132/iso-2631-1-1997

International Organization for Standardization (ISO) (2009) ISO 9612: Acoustics-Determination of occupational noise exposure-Engineering method. Available at: https://standards.iteh.ai/catalog/standards/sist/cfaf73ce-cba2-4982-bd71-49641b4085df/iso-9612-2009

International Organization for Standardization (ISO) (2013) ISO 1999-2013: Acoustics-Estimation of noise-induced hearing loss. Available at: https://standards.iteh.ai/catalog/standards/sist/c7a43ade-865c-42b5-95fd-697f5f0365c4/Webwww.iso.org https://standards.iteh.ai/catalog/standards/sist/c7a43ade-865c-42b5-95fd-697f5f0365c4/

International Organization for Standardization (ISO) (2018) ISO 2631-5: Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration — Part 5: Method for evaluation of vibration containing multiple shocks. Available at: https://standards.iteh.ai/catalog/standards/iso/7cc323db-d6e2-4be3-8776-e8f0ba4649c2/iso-2631-5-2018

James S (2005) Defining the cockpit noise hazard, aircrew hearing damage risk and the benefits active noise reduction headsets can provide. Available at: https://www.researchgate.net/publication/235198728_Defining_the_Cockpit_Noise_Hazard_Aircrew_Hearing_Damage_Risk_and_the_Benefits_Active_Noise_Reduction_Headsets_Can_Provide

Jaruchinda P, Thongdeetae T, Panichkul S, Hanchumpol P (2005) Prevalence and an analysis of noise: induced hearing loss in army helicopter pilots and aircraft mechanics. J Med Assoc Thai 88(Suppl. 3):S232-9.

Kåsin JI, Mansfield N, Wagstaff A (2011) Whole body vibration in helicopters: Risk assessment in relation to low back pain. Aviat Space Environ Med 82(8):790-6. https://doi.org/10.3357/ASEM.2982.2011

Kato Y, Endo H, Kizuka T (2009) Mental fatigue and impaired response processes: Event-related brain potentials in a Go/No Go task. Int J Psychophysiol 72(2):204-11. https://doi.org/10.1016/j.ijpsycho.2008.12.008

King RB, Saliba AJ, Creed DC, Brock JR (1996) Assessment of noise levels in and around the Sikorsky S-7OA-9 black hawk helicopter. DSTO Aeronautical and Maritime Research Laboratory. Available at: https://www.researchgate.net/publication/27254633_Assessment_of_Noise_Levels_in_and_Around_the_Sikorsky_S-7OA-9_Black_Hawk_Helicopter

Kittusamy NK, Buchholz B (2004) Whole-body vibration and postural stress among operators of construction equipment: A literature review. J Safety Res 35(3):255-61. https://doi.org/10.1016/j.jsr.2004.03.014

Kuronen P, Toppila E, Starck J, Pääkkönen R, Sorri MJ (2004) Modelling the risk of noise-induced hearing loss among military pilots. Int J Audiol 43(2):79-84. https://doi.org/10.1080/14992020400050013

Ladner TJ (1997) Back pain and endurance training of back muscles: justification for further study in helicopter pilots. Available at: https://www.semanticscholar.org/paper/Back-Pain-and-Endurance-Training-of-Back-Muscles%3A-Ladner/14a4ffd62ac8eda1e6e10a41060afe3357593d7d

Lovesey EJ (1979). Environmental effects upon helicopter crew. Fifth European Rotorcraft and Powered Lift Aircraft Forum, Amsterdam, the Netherlands. Available at: https://dspace-erf.nlr.nl/server/api/core/bitstreams/618d2018-ea18-4738-9e8c-52922213d0b6/content

Lowson MV, Ollerhead JB (1969) A theoretical study of helicopter rotor noise. J Sound Vib 9(2):197-222. https://doi.org/10.1016/0022-460X(69)90028-5

Majumder S, Deen MJ (2019) Smartphone sensors for health monitoring and diagnosis. Sensors 19(9):2164. https://doi.org/10.3390/s19092164

Mansfield NJ (2004) Human response to vibration. CRC Press.

Martinez M, Yanishevsky M, Rocha B, Groves RM, Bellinger N (2015) Maintenance and monitoring of composite helicopter structures and materials. In: Beaumont PWR, Soutis C, Hodzic A, editors. Structural integrity and durability of advanced composites: innovative modelling methods and intelligent design Elsevier. p. 540-78. https://doi.org/10.1016/B978-0-08-100137-0.00021-3

Mckinley RL, Bjorn VS, Hall JA (n.d.) Improved hearing protection for aviation personnel. Available at: https://publications.sto.nato.int/publications/STO%20Meeting%20Proceedings/RTO-MP-HFM-123/MP-HFM-123-13.pdf

McMahon TW, Newman DG (2018) The differential effect of sustained operations on psychomotor skills of helicopter pilots. Aerosp Med Hum Perform 89(6):496-502. https://doi.org/10.3357/AMHP.4895.2018

McReynolds MC (2005) Noise-induced hearing loss. Air Medical J 24(2):73-8. https://doi.org/10.1016/j.amj.2004.12.005

Panjabi MM, Andersson GBJ, Jorneus L, Hult E, Mattsson L (1986) In vivo measurements of spinal column vibrations. J Bone Joint Surg Series A 68(5):695-702. https://doi.org/10.2106/00004623-198668050-00009

Pawar PM, Ganguli R (2007) On the effect of progressive damage on composite helicopter rotor system behavior. Compos Struct 78(3):410-23. https://doi.org/10.1016/j.compstruct.2005.11.043

Pei L, Jiao S, Chen R, Liu J, Chen W, Kuusniemi H, Tenhunen T, Kröger T, Chen Y, Leppäkoski H, Takala J (2010). Motion recognition assisted indoor wireless navigation on a mobile phone. Available at: https://www.researchgate.net/publication/261876649

Piňosová M, Andrejiová M, Badida M, Moravec M (2018) Analysis and evaluation of risks from exposure to noise in a working environment. Acta Mech Slovaca 22(3):44-52. https://doi.org/10.21496/ams.2018.026

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Pope MH, Wilder DG, Jorneus L, Broman H, Svensson M, Andersson G (1987) The response of the seated human to sinusoidal vibration and impact. J Biomech Eng 109(4):279-84. https://doi.org/10.1115/1.3138681

Pope MH, Wilder DG, Seroussi RE, Donnermeyer DD (1985) The effects of helicopter vibration on the spinal system. Available at: https://apps.dtic.mil/sti/tr/pdf/ADA181434.pdf

Reddy RRK, Ganguli R (2003) Structural damage detection in a helicopter rotor blade using radial basis function neural networks. Smart Mater Struct 12:232-41. https://doi.org/10.1088/0964-1726/12/2/311

Reinhart RO (2008). Basic flight physiology. 3rd ed. McGraw Hill.

Santos FLM, Peeters B, Van der Auweraer H, Góes LCS, Desmet W (2016) Vibration-based damage detection for a composite helicopter main rotor blade. Case Stud Mech Syst Signal Process 3:22-7. https://doi.org/10.1016/j.csmssp.2016.01.001

Seidel H, Bastek R, Brauer D, Buchholz C, Meister A, Metz AM, Rothe R (1980) On human response to prolonged repeated whole-body vibration. Ergonomics 23(3):191-211. https://doi.org/10.1080/00140138008924734

Shappell SA, Wiegmann DA (2000) The human factors analysis and classification system – HFACS. Available at: https://commons.erau.edu/cgi/viewcontent.cgi?article=1777&context=publication

Sirevaag EJ, Kramer AF, Wickens CD, Reisweber M, Strayer DL, Grenell JF (1993) Assessment of pilot performance and mental workload in rotary wing aircraft. Ergonomics 36(9):1121-40. https://doi.org/10.1080/00140139308967983

Smith SCSCJ (2019) Vibration Exposure Characterization and health risk assessment of the UH-60L Blackhawk. Available at: https://apps.dtic.mil/sti/pdfs/AD1082363.pdf

Sneddon A, Mearns K, Flin R (2013) Stress, fatigue, situation awareness and safety in offshore drilling crews. Safety Sci 56:80-8. https://doi.org/10.1016/j.ssci.2012.05.027

Stave A (1973) Effects of helicopter noise and vibration on pilot performance. NASA Contractor Report.

Tamer A, Zanoni A, Cocco A, Masarati P (2021) A generalized index for the assessment of helicopter pilot vibration exposure. Vibration 4(1):133-50. https://doi.org/10.3390/vibration4010012

Teixeira CLD (2020) Helicopter pilot rostering on/off schedule scheme in Angola oil and gas offshore industry [Master's degree thesis]. ISEC. Available at: https://comum.rcaap.pt/entities/publication/8a4b9daf-e9f0-4a15-a14a-30e837733d3f

United States. Department of Transportation. Federal Aviation Administration (FAA) (2004) Report to Congress: Nonmilitary Helicopter Urban Noise Study. United States of America: FAA. Available at: https://rosap.ntl.bts.gov/view/dot/9814

U.S. Department of Health and Human Services (1998) Occupational Noise Exposure: Revised Criteria. National Institute for Occupational Safety and Health. Available at: https://stacks.cdc.gov/view/cdc/6376

Wannenburg J, Malekian R (2017) Physical activity recognition from smartphone accelerometer data for user context awareness sensing. IEEE Trans Syst Man Cybernet Syst 47(12):3142-9. https://doi.org/10.1109/TSMC.2016.2562509

Zadoń H, Nowakowska-Lipiec K, Michnik R (2021) A sitting or standing position – which one exerts more loads on the musculoskeletal system of the lumbar spine? Comparative tests based on the methods of mathematical modelling. Acta Bioeng Biomech 23(1):113-20. https://doi.org/10.37190/ABB-01762-2020-01