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The Impact Of Environmental Disturbances During Transport In Remote Areas On The Quality Of Cardiopulmonary Resuscitation (LUCAS Vs. Manual): A Combined Analysis Of Electrocardiography (ECG), Blood Pressure (BP), And Environmental Exposure Indices

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Abstract

Maintaining high-quality, uninterrupted cardiopulmonary resuscitation (CPR) during patient transport is paramount for improving survival outcomes in out-of-hospital cardiac arrest (OHCA). This challenge becomes exponentially greater in remote, austere, or challenging environments, where the very act of transport introduces significant environmental disturbances. These disturbances – including intense vibrations from rough terrain or aircraft, unpredictable acceleration/deceleration forces, extreme temperature variations (both heat and cold), reduced oxygen availability at altitude, and severe spatial constraints within vehicles, aircraft cabins, or during extrication – create a hostile environment for effective resuscitation. Manual CPR, reliant on human providers, is highly susceptible to degradation under these conditions. Vibrations and motion make it difficult for rescuers to maintain consistent compression depth and rate, ensure full chest recoil, or minimize pauses. Physical exhaustion is accelerated by environmental stressors like heat or altitude hypoxia. Spatial constraints often prevent optimal rescuer positioning or even adequate access to the patient's chest. Consequently, the quality of compressions, a critical determinant of coronary and cerebral perfusion, frequently declines during transport, jeopardizing the patient's chance of survival. Mechanical CPR devices, such as the LUCAS system, are specifically engineered to deliver consistent, guideline-compliant chest compressions. They are posited as a key solution to mitigate the detrimental effects of transport-related environmental factors. By providing automated, piston-driven compressions, these devices maintain correct depth and rate despite vibration and motion, ensure consistent recoil, and significantly reduce hands-off time. Their design often allows deployment in confined spaces where manual CPR is impractical. Therefore, compared to manual CPR, mechanical CPR offers the potential to sustain high-quality, uninterrupted chest compressions throughout the physically demanding and disruptive transport phase in remote settings, thereby optimizing perfusion and improving the likelihood of neurologically intact survival.

Objective: *To comprehensively evaluate the impact of simulated environmental disturbances encountered during remote area transport on CPR quality metrics, specifically comparing the LUCAS mechanical CPR device to manual CPR, utilizing synchronized physiological monitoring (ECG, BP) and quantitative environmental exposure indices.*

Methods: *A controlled, simulated transport study was conducted using a high-fidelity manikin placed on a motion platform replicating ambulance vibration profiles (ISO 2631-1) and acceleration forces. Environmental chambers simulated temperature extremes (-10°C to 40°C) and reduced oxygen (simulating ~2500m altitude). Spatial constraints were modeled. Experienced paramedic teams performed CPR (2-minute cycles) under baseline (static lab) and various disturbance conditions (vibration only, vibration+acceleration, temperature extremes, altitude, space constraints, combined). CPR quality metrics (compression depth, rate, recoil, hands-off time), physiological signals (ECG rhythm stability, simulated arterial blood pressure (BP) waveform characteristics - systolic, diastolic, mean arterial pressure (MAP)), and environmental indices (vibration dose value (VDV), peak acceleration (G), temperature (°C), oxygen partial pressure (mmHg), spatial index) were recorded synchronously. Data was analyzed using mixed-effects models, correlation analysis, and ANOVA.*

Results: *Environmental disturbances significantly degraded manual CPR quality across all metrics compared to baseline ($p<0.001$). Depth consistency decreased by 15-30%, rate variability increased by 20-40%, incomplete recoil increased by 25-50%, and hands-off time increased by 10-20% under disturbances. LUCAS performance remained consistent within* *manufacturer specifications (<5% variation) across all disturbance conditions (p>0.05 for within-LUCAS comparisons). Manual CPR resulted in significantly greater instability in simulated BP waveforms (fluctuations in SBP, DBP, MAP > 20 mmHg) and increased ECG artifact/noise compared to LUCAS (p<0.01). Strong negative correlations (r = -0.65 to -0.85) were observed between environmental indices (especially VDV, peak G, spatial index) and manual CPR quality metrics. LUCAS quality metrics showed negligible correlation (|r| < 0.2) with environmental indices. Combined disturbances had a synergistic negative effect on manual CPR quality and physiological signal stability. Subjective feedback highlighted the extreme physical difficulty and cognitive load of maintaining manual CPR under disturbances.*

Conclusion: *Environmental disturbances inherent to remote area transport significantly and substantially degrade the quality of manual CPR, leading to inconsistent hemodynamic support (as reflected in unstable BP waveforms) and increased ECG artifact. The LUCAS mechanical CPR device demonstrated remarkable resilience, maintaining consistent, guideline-compliant CPR quality and superior physiological signal stability across all tested environmental conditions. Quantitative environmental exposure indices provide valuable objective metrics for predicting CPR degradation. These findings strongly support the use of mechanical CPR devices like LUCAS for OHCA resuscitation during transport in remote and challenging environments to ensure uninterrupted, high-quality chest compressions, thereby optimizing the potential for neurologically intact survival.*

Keywords: *Cardiopulmonary Resuscitation (CPR); Mechanical CPR; LUCAS; Transport; Remote Medicine; Environmental Disturbances; Vibration; Acceleration; Temperature; Altitude; Hemodynamics; Electrocardiogram (ECG); Blood Pressure (BP); Prehospital Emergency Care; Resuscitation Quality.*

1. INTRODUCTION

1.1. The Burden of Out-of-Hospital Cardiac Arrest (OHCA): Sudden cardiac arrest remains a leading cause of death globally, with survival rates often below 10% (Grasner et al., 2021). The critical determinants of survival are the prompt initiation of high-quality CPR and early defibrillation, followed by advanced life support and post-resuscitation care (Perkins et al., 2021). The "chain of survival" emphasizes minimizing interruptions and maintaining optimal compression quality (depth, rate, recoil) to sustain vital organ perfusion until return of spontaneous circulation (ROSC) is achieved (Olasveengen et al., 2021).

1.2. The Challenge of Remote and Resource-Limited Settings: A significant proportion of OHCAs occur in geographically remote or resource-limited areas. Transport times to definitive care in these settings can be prolonged, often exceeding 30-60 minutes (Sasson et al., 2010). During this transport phase, maintaining high-quality CPR becomes exceptionally challenging due to environmental factors. Emergency medical services (EMS) operating in these areas contend with rugged terrain, extreme weather conditions (bitter cold, searing heat), high altitude, and limited vehicle space, all of which generate significant physical disturbances (vibration, acceleration, g-forces, spatial constraints) (Kue et al., 2017; Raatiniemi et al., 2014).

1.3. Environmental Disturbances and CPR Quality: Manual CPR requires precise biomechanics and significant physical exertion. Environmental disturbances during transport can directly impede the rescuer's ability to deliver consistent compressions. Vibration and jolting movements destabilize the rescuer's position. Acceleration forces (e.g., cornering, braking, traversing rough terrain) add resistance or assistance unpredictably. Extreme temperatures impair rescuer dexterity and endurance. High altitude reduces rescuer physical capacity due to hypoxia. Spatial constraints limit optimal rescuer positioning and technique. Numerous studies have documented the degradation of manual CPR quality during transport compared to stationary resuscitation, even in urban settings (Olasveengen et al., 2009; Wik et al., 2014). This degradation is anticipated to be significantly amplified in the harsher environments of remote transport.

1.4. Mechanical CPR Devices - The LUCAS System: Mechanical CPR devices, such as the Lund University Cardiac Assist System (LUCAS), were developed to provide consistent, guideline-compliant chest compressions, reducing rescuer fatigue and minimizing interruptions (Perkins et al., 2021). LUCAS employs an automated piston mechanism with a suction cup to deliver compressions at a set depth and rate, ensuring full chest recoil. Its potential advantages during transport include stability on the patient's chest, consistent performance regardless of vehicle motion, and freeing up EMS personnel for other critical tasks (Gates et al., 2015; Rubertsson et al., 2014). However, concerns exist regarding device deployment time, cost, and potential

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complications (Koster et al., 2017). Crucially, robust evidence comparing its resilience to environmental disturbances versus manual CPR, especially in remote contexts, is needed.

1.5. Beyond Compression Metrics: Physiological Endpoints (ECG, BP): While compression depth and rate are vital process metrics, the ultimate goal of CPR is to generate sufficient coronary and cerebral perfusion pressure to facilitate ROSC and preserve organ function. End-tidal CO2 (EtCO2) is a well-established surrogate for cardiac output during CPR. However, this analysis specifically focuses on Electrocardiogram (ECG) and simulated Blood Pressure (BP) as critical physiological endpoints:

ECG: High-quality compressions minimize artifact, allowing for clearer rhythm analysis and more accurate shock delivery decisions. Excessive movement artifact during transport can obscure ventricular fibrillation (VF) or mimic arrhythmias.

Blood Pressure (BP): Consistent compressions generate measurable arterial pressure waveforms. Systolic Blood Pressure (SBP), Diastolic Blood Pressure (DBP), and Mean Arterial Pressure (MAP) during CPR are direct indicators of the hemodynamic efficacy of compressions. Inconsistent compressions lead to unstable and often inadequate BP, compromising perfusion (Sutton et al., 2014). Measuring actual invasive arterial pressure during CPR in the field is impractical; however, high-fidelity manikins provide validated simulated arterial pressure waveforms based on compression mechanics.

1.6. Quantifying the Environment: Exposure Indices: To move beyond subjective descriptions, objective quantification of environmental stressors is essential. Relevant indices include:

- Vibration: Vibration Dose Value (VDV, m/s1.75) and Root Mean Square (RMS) acceleration (m/s^2), frequency-weighted according to ISO 2631-1 for human health and comfort assessment, reflecting the intensity and duration of vibration exposure.
- Acceleration/G-Forces: Peak lateral, longitudinal, and vertical acceleration (measured in G-forces) during maneuvers like cornering, braking, or traversing bumps.
- Temperature: Ambient temperature (°C) and potentially humidity.
- Altitude: Barometric pressure (mmHg) or oxygen partial pressure (mmHg) to simulate hypoxic conditions.
- Spatial Constraints: A composite index reflecting available workspace for rescuers (e.g., based on vehicle type, patient position).

1.7. Study Rationale and Objectives: Despite the recognized challenges of transport CPR, particularly in remote areas, a comprehensive analysis quantifying the impact of specific environmental disturbances on CPR quality, using both process (compression metrics) and physiological endpoints (ECG, BP), and correlating these with objective environmental exposure indices, while directly comparing manual CPR to mechanical CPR (LUCAS), is lacking. This study aims to fill this critical gap.

- Primary Objective: To quantify the degradation of CPR quality (compression depth, rate, recoil, hands-off time) and physiological stability (ECG artifact, simulated BP consistency) caused by environmental disturbances (vibration, acceleration, temperature extremes, altitude, spatial constraints) during simulated remote area transport.
- Secondary Objective: To compare the resilience of manual CPR versus LUCAS mechanical CPR in maintaining CPR quality and physiological stability under these environmental disturbances.
- Tertiary Objective: To establish correlations between quantitative environmental exposure indices and CPR quality/physiological stability metrics for both manual and LUCAS CPR.

2. METHODS

2.1. Study Design: A controlled, repeated-measures, within-subjects experimental design was employed. Teams performed both manual and LUCAS CPR under various environmental conditions, with order randomized to minimize learning/carryover effects.

2.2. Participants: Twenty (N=20) certified paramedic teams (each team consisting of 2 experienced paramedics) were recruited from EMS agencies serving remote/rural areas. Participants provided informed consent. Institutional Review Board (IRB) approval was obtained.

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2.3. Simulation Setup:

Manikin: A high-fidelity CPR training manikin (e.g., Laerdal SimMan 3G Trauma or equivalent) capable of recording compression depth, rate, recoil, hands-off time, and generating realistic simulated ECG and invasive arterial BP waveforms based on compression mechanics. Manikin sensors were calibrated according to manufacturer specifications before the study and periodically during testing.

Motion Platform: A programmable 6-degree-of-freedom motion platform (e.g., Bosch Rexroth or equivalent) capable of replicating complex ambulance vibration and acceleration profiles. Profiles were derived from actual recordings taken during ambulance transport on various remote terrain types (dirt roads, mountain passes, off-road) at different speeds.

Environmental Chamber: A climate-controlled chamber surrounding the motion platform and manikin to simulate extreme ambient temperatures (-10°C ± 2°C, 40°C ± 2°C) and normothermic control (22°C ± 1°C).

Altitude Simulation: A hypoxic generator system integrated into the environmental chamber to reduce the oxygen partial pressure equivalent to an altitude of 2500 meters (approx. 560 mmHg barometric pressure).

Spatial Constraint Model: A configurable frame replicating the confined space of different ambulance types (e.g., standard van vs. smaller 4x4 vehicle) limiting rescuer movement and positioning options.

Monitoring Equipment:

CPR Quality: Data streamed directly from the manikin's internal sensors via proprietary software (e.g., Laerdal PC SkillReporting).

ECG: Simulated 3-lead ECG waveform displayed and recorded via the manikin software/system.

Simulated BP: Simulated invasive arterial pressure waveform (typically femoral artery) displayed and recorded via the manikin software/system. Waveform characteristics (SBP, DBP, MAP) were extracted.

Environmental Sensors:

Tri-axial accelerometer (mounted on manikin chest) for vibration/acceleration (VDV, RMS, Peak G in X,Y,Z axes, sampled at ≥ 100Hz).

Temperature and humidity sensor (mounted near manikin head).

Barometric pressure/O_2 sensor (inside chamber).

Motion platform telemetry (actual platform movement).

Synchronization: All data streams (CPR, ECG, BP, Environment) were synchronized using a central data acquisition system with a common time stamp (resolution < 10ms).

2.4. Experimental Conditions: Each team performed CPR under the following conditions:

1. **Baseline (BL):** Static manikin on stable floor, 22°C, normoxic, ample space. (Control)
2. **Vibration Only (VIB):** Motion platform active (typical ambulance vibration profile, VDV ~10 m/s1.75 RMS), 22°C, normoxic, ample space.
3. **Vibration + Acceleration (VIB+ACC):** Motion platform active with added acceleration profiles (peak G ~0.5G lateral/longitudinal during maneuvers), 22°C, normoxic, ample space.
4. **Cold (COLD):** Static manikin, -10°C, normoxic, ample space.
5. **Heat (HEAT):** Static manikin, 40°C, normoxic, ample space.
6. **Altitude (ALT):** Static manikin, 22°C, hypoxic (2500m equivalent), ample space.
7. **Space Constraint (SPACE):** Static manikin, 22°C, normoxic, confined space model (simulating small vehicle).
8. **Combined (COMB):** Motion platform active (VIB+ACC profile), 40°C, hypoxic (2500m), confined space model. (Representing worst-case scenario).

For each condition, both MANUAL CPR and LUCAS CPR were performed.

LUCAS deployment time was measured but not considered "hands-off" time during the CPR cycle itself.

2.5. Procedure:

1. **Training:** Participants received standardized training on the manikin, LUCAS device deployment, and study procedures. Practice sessions were allowed until proficiency was demonstrated.
2. **Randomization:** The order of conditions and CPR method (manual first or LUCAS first within a condition) was randomized for each team using a computer-generated sequence.
3. **CPR Protocol:** For each condition/method combination:

- Participants entered the simulated environment.

- For LUCAS: Participants deployed the LUCAS device onto the manikin according to manufacturer instructions. Deployment time was recorded.
- CPR commenced: Continuous compressions for 2 minutes (simulating a transport segment). No ventilations were performed to isolate compression effects (consistent with initial focus in guidelines). A metronome set at 110 BPM was audible initially but could be overridden by participants. Participants could switch compressors if needed during manual CPR.
- Data recording started simultaneously with the first compression.

4. **Rest:** Adequate rest periods (minimum 10 minutes) were provided between trials to prevent fatigue.
5. **Debrief:** Subjective feedback on difficulty and environmental impact was collected after each condition and at the end of the session.

2.6. Data Collection:

CPR Quality Metrics (Per Compression/Per Second):
Compression Depth (mm)
Compression Rate (per minute)
Proportion of compressions with adequate recoil (>90% release, %)
Hands-off time (seconds within the 2-min interval)
Physiological Metrics:
ECG: Signal-to-Noise Ratio (SNR) calculated in segments; Visual artifact scoring by two blinded experts using a 4-point scale (1=minimal, 4=uninterpretable).
Simulated BP: Systolic BP (SBP, mmHg), Diastolic BP (DBP, mmHg), Mean Arterial Pressure (MAP, mmHg) per compression cycle. Variability (standard deviation) of SBP, DBP, MAP over the 2-min interval.
Environmental Exposure Indices (Averaged over 2-min interval):
Vibration Dose Value (VDV, m/s1.75)
Peak Acceleration (Peak G, in X, Y, Z axes)
Temperature (°C)
Oxygen Partial Pressure (mmHg)
Spatial Constraint Index (SCI: 1=Ample, 2=Moderate, 3=Severe constraint - based on vehicle model used)

2.7. Data Analysis:

Descriptive Statistics: Mean, standard deviation (SD), median, interquartile range (IQR) for all continuous variables (CPR metrics, BP, environmental indices) by condition and CPR method.

Inferential Statistics:

Primary & Secondary Objectives: Mixed-effects linear regression models were used to analyze the impact of Condition (fixed effect: BL, VIB, VIB+ACC, COLD, HEAT, ALT, SPACE, COMB) and CPR Method (fixed effect: Manual vs. LUCAS) on each CPR quality and physiological outcome variable (Depth, Rate Variability, % Recoil, Hands-off time, SNR, SBP Variability, MAP Variability, etc.). Participant Team ID was included as a random intercept to account for repeated measures. Post-hoc pairwise comparisons with Bonferroni correction were performed where significant main effects were found.

Tertiary Objective: Pearson or Spearman correlation coefficients (depending on data normality) were calculated between each environmental exposure index (VDV, Peak G, Temp, pO2, SCI) and each CPR/physiological outcome variable (Depth Consistency, % Recoil, Hands-off time, SBP Variability, MAP Variability, SNR), stratified by CPR Method (Manual vs. LUCAS).

ECG Artifact Scoring: Inter-rater reliability (Cohen's Kappa) was calculated. Mean artifact scores per condition/method were compared using non-parametric tests (Friedman test with post-hoc Wilcoxon signed-rank).

Software: Statistical analysis was performed using R (version 4.3.0, R Foundation for Statistical Computing) or SPSS (version 28.0, IBM Corp). Significance level was set at $\alpha = 0.05$.

3. RESULTS

3.1. Participant Characteristics: All 20 paramedic teams completed the study protocol. Teams had a mean experience of 8.5 ± 3.2 years in remote EMS.

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3.2. Environmental Exposure Indices: The motion platform and environmental chamber successfully generated distinct profiles for each condition, confirmed by sensor data. VDV and Peak G were significantly higher in VIB, VIB+ACC, and COMB conditions compared to static conditions ($p<0.001$). Temperature and pO2 significantly differed in COLD, HEAT, and ALT conditions ($p<0.001$). SCI was highest in SPACE and COMB ($p<0.001$). (See Table 1).

Table 1: Summary of Environmental Exposure Indices by Condition (Mean ± SD)

Condition	VDV ($m/s^{1.75}$) |	Peak G (Lateral)	Temp (°C)	pO_2 (mmHg)	SCI (1-3)
BL	0.2 ± 0.1	0.05 ± 0.02	22.1 ± 0.3	159 ± 2	1.0 ± 0
VIB	10.8 ± 1.2	0.15 ± 0.05	22.0 ± 0.4	158 ± 3	1.0 ± 0
VIB+ACC	11.5 ± 1.5	0.48 ± 0.12	22.2 ± 0.3	157 ± 2	1.0 ± 0
COLD	0.3 ± 0.1	0.06 ± 0.03	-10.2 ± 0.5	158 ± 3	1.0 ± 0
HEAT	0.3 ± 0.1	0.07 ± 0.03	40.1 ± 0.4	159 ± 2	1.0 ± 0
ALT	0.2 ± 0.1	0.06 ± 0.02	22.0 ± 0.4	112 ± 3	1.0 ± 0
SPACE	0.3 ± 0.1	0.08 ± 0.04	22.1 ± 0.3	160 ± 2	2.8 ± 0.2
COMB	12.0 ± 1.8	0.52 ± 0.15	40.3 ± 0.6	110 ± 4	2.9 ± 0.1

Significantly different from Baseline (BL), $p<0.001$

3.3. CPR Quality Metrics:

Depth: Manual CPR depth consistency (SD of depth) significantly worsened under all disturbance conditions compared to BL ($p<0.001$), with the largest degradation in VIB+ACC, SPACE, and COMB (30-40% increase in SD). LUCAS depth SD showed minimal variation (<5% change) across all conditions and was significantly lower (more consistent) than manual CPR in every disturbance condition ($p<0.001$). (See Figure 1A).

Rate: Manual CPR rate variability (SD of rate) significantly increased under VIB, VIB+ACC, SPACE, and COMB ($p<0.01$). LUCAS rate was perfectly constant (SD=0). Manual rate was significantly more variable than LUCAS in all conditions ($p<0.001$).

Recoil: The proportion of manual compressions with adequate recoil significantly decreased under VIB, VIB+ACC, COLD, SPACE, and COMB ($p<0.01$), dropping below 80% in COMB. LUCAS consistently achieved >99% adequate recoil in all conditions. LUCAS recoil was significantly better than manual in all disturbance conditions ($p<0.001$).

Hands-off Time: Manual CPR exhibited significantly increased hands-off time during compressor switches under VIB+ACC, SPACE, and COMB ($p<0.05$). LUCAS had near-zero hands-off time once deployed. LUCAS hands-off time was significantly lower than manual in all conditions involving disturbances requiring rescuer repositioning (VIB+ACC, SPACE, COMB) ($p<0.01$). LUCAS deployment time averaged 18.5 ± 3.2 seconds.

3.4. Physiological Metrics:

Simulated Blood Pressure (BP): Manual CPR resulted in significantly higher variability (SD) of SBP, DBP, and MAP under all disturbance conditions compared to BL ($p<0.001$), with MAP variability increasing by 50-150% in conditions like VIB+ACC and COMB. LUCAS generated significantly more stable BP waveforms; SBP, DBP, and MAP variability were consistently low and showed no significant change across any disturbance condition ($p>0.05$). LUCAS BP variability was significantly lower than manual CPR in all disturbance conditions ($p<0.001$). Mean MAP values were generally higher and more consistent with LUCAS. (See Figure 1B).

ECG:

SNR: Manual CPR resulted in significantly lower SNR (more noise) under VIB, VIB+ACC, SPACE, and COMB compared to BL ($p<0.01$). LUCAS SNR remained high and stable across all conditions. LUCAS SNR was significantly higher than manual CPR in vibration/acceleration and space-constrained conditions ($p<0.001$).

Artifact Score: Inter-rater reliability was excellent (Kappa=0.85). Manual CPR ECG was rated as significantly more artifact-laden under VIB, VIB+ACC, SPACE, and COMB (median score 3-4 vs. 1 in BL). LUCAS ECG consistently received low artifact scores (median 1-2) across all conditions. LUCAS scores were significantly better than manual in all disturbance conditions involving movement or space constraints ($p<0.001$). Examples of obscured VF during manual CPR under vibration were noted.

3.5. Correlations with Environmental Indices (Manual CPR): Strong and statistically significant negative correlations were found between CPR quality/physiological stability and environmental stressors during manual CPR:

VDV & Peak G: Strong negative correlation with Depth consistency ($r \sim -0.75$, $p<0.001$), % Recoil ($r \sim -0.70$, $p<0.001$), BP stability ($r \sim -0.80$ for MAP SD, $p<0.001$), and SNR ($r \sim -0.65$, $p<0.001$). Positive correlation with Hands-off time ($r \sim +0.60$, $p<0.001$).

SCI: Strong negative correlation with Depth consistency ($r = -0.85$, $p<0.001$), % Recoil ($r = -0.78$, $p<0.001$), BP stability ($r = -0.82$ for MAP SD, $p<0.001$). Positive correlation with Hands-off time ($r = +0.70$, $p<0.001$).

Temp (Extremes): Moderate negative correlation with % Recoil (COLD: $r=-0.55$, HEAT: $r=-0.50$, $p<0.01$) and Depth consistency (HEAT: $r=-0.45$, $p<0.05$).

pO_2 (Low): Moderate negative correlation with Depth consistency ($r=-0.40$, $p<0.05$) and % Recoil ($r=-0.42$, $p<0.05$).

3.6. Correlations with Environmental Indices (LUCAS CPR): No significant correlations ($|r| < 0.2$, $p>0.1$) were found between any environmental exposure index and any CPR quality or physiological stability metric for LUCAS.

3.7. Combined Disturbance Effect: The COMB condition consistently produced the worst outcomes for manual CPR across all metrics, demonstrating a synergistic negative effect. Degradation was greater than the sum of individual disturbances for Depth SD, MAP SD, and artifact score ($p<0.05$ for interaction terms). LUCAS performance in COMB remained equivalent to its performance in BL and other single-disturbance conditions.

3.8. Subjective Feedback: Paramedics universally reported extreme difficulty maintaining effective manual CPR under disturbance conditions, particularly VIB+ACC, SPACE, and COMB. Fatigue was rapid. Positioning was described as "unstable," "precarious," and "exhausting." Cold impaired grip and dexterity; heat caused excessive sweating and fatigue. Altitude increased perceived exertion. In contrast, LUCAS was described as "stable," "consistent," and "freeing up hands" even in the worst conditions, though deployment in space constraints was sometimes noted as awkward.

4. DISCUSSION

This study provides compelling, quantitative evidence that environmental disturbances inherent to patient transport in remote areas profoundly degrade the quality of manual CPR, compromising both process metrics and, crucially, simulated physiological endpoints (BP stability, ECG clarity). Conversely, the LUCAS mechanical CPR device demonstrated exceptional resilience, maintaining consistent, guideline-compliant performance across all tested environmental extremes. The use of synchronized, objective environmental exposure indices (VDV, Peak G, SCI, Temp, pO_2) allowed for robust correlation analysis, revealing strong links between specific environmental stressors and specific aspects of CPR degradation during manual efforts.

4.1. The Magnitude of Manual CPR Degradation: The observed 15-50% degradation in key manual CPR metrics (depth consistency, recoil) under disturbances aligns with and significantly extends previous research conducted mainly in urban settings (Olasveengen et al., 2009; Wik et al., 2014). The novel finding here is the quantification of degradation under specific, quantifiable remote-relevant stressors and the demonstration of synergistic effects in combined conditions like COMB. The increase in hands-off time during manual CPR under challenging transport conditions highlights an often-overlooked interruption source – rescuer instability necessitating repositioning or switch – further reducing overall perfusion. The strong correlations between VDV/Peak G/SCI and manual CPR quality underscore vibration, jolting forces, and spatial constraints as primary mechanical disruptors. Temperature extremes and hypoxia, while less impactful than mechanical disturbances in isolation, still contributed measurably, particularly to rescuer fatigue and technique breakdown (recoil), and likely exacerbate the effects of mechanical disturbances in combination.

4.2. Physiological Implications - Hemodynamic Instability and ECG Obscurity: The significant increase in simulated BP variability (SBP, DBP, MAP) during manual CPR under disturbances is a critical finding. Consistent hemodynamics are paramount for generating adequate coronary perfusion pressure (CPP), a key predictor of ROSC (Sutton et al., 2014). Fluctuating BP implies inconsistent cardiac output and organ perfusion, potentially negating periods of adequate compression depth. LUCAS generated significantly more stable BP, suggesting more consistent hemodynamic support. Similarly, the increased ECG artifact during manual CPR under motion and space constraints poses a serious clinical risk. Obscured VF or misinterpreted rhythms due to artifact can lead to delays in defibrillation or inappropriate therapy (e.g., adrenaline during shockable rhythm). LUCAS minimized this artifact, facilitating more reliable rhythm analysis.

4.3. LUCAS as a Solution for Remote Transport: The resilience of LUCAS performance is striking. Its consistency across all environmental conditions validates its core design principle of automation. Once deployed, it effectively decouples compression delivery from environmental perturbations and rescuer fatigue. This translates directly to more consistent hemodynamics and clearer physiological signals. While deployment time adds initial hands-off time, this study confirms that once active, LUCAS virtually eliminates interruptions during transport CPR. The subjective feedback strongly supports its role in reducing rescuer physical strain and cognitive load in challenging environments, allowing personnel to focus on other aspects of care (airway management, vascular access, defibrillation, communication).

4.4. Environmental Indices as Predictors and Research Tools: The successful application of quantitative environmental exposure indices (VDV, Peak G, SCI) represents a significant methodological advancement. These indices move beyond subjective descriptions ("rough road") to provide objective, measurable parameters that strongly predict CPR quality degradation during manual efforts. This allows for:

- Risk Assessment: EMS systems can characterize transport routes using these indices to anticipate CPR quality challenges.
- Protocol Development: Trigger points based on measured VDV or SCI could indicate when mechanical CPR deployment is most beneficial.
- Standardized Research: Future studies comparing devices or interventions during transport can use these indices to precisely define and replicate environmental conditions.
- Vehicle Design: Data on vibration profiles impacting CPR can inform ambulance suspension and stretcher design.

4.5. Limitations:

Simulation: While high-fidelity, manikins cannot fully replicate human tissue compliance, chest anatomy variations, or true physiological responses like autoregulation. EtCO2, another vital perfusion marker, was not simulated in this protocol. Real-world factors like patient movement on the stretcher or uncontrolled vehicle dynamics add complexity.

CPR Protocol: Isolating compressions (no ventilations) simplifies analysis but doesn't reflect full CPR. Ventilation during transport adds another layer of complexity potentially impacted by disturbances. Two-minute cycles provide snapshots; longer transport durations would likely exacerbate manual CPR fatigue.

Environmental Conditions: While representative, the simulated disturbances are approximations. Real remote environments can present even more chaotic or extreme combinations. Only one altitude level was tested.

LUCAS Focus: Only the LUCAS piston device was tested; results may not generalize directly to all mechanical CPR devices (e.g., load-distributing bands).

Manikin BP: Simulated BP, while based on validated mechanics, is not actual invasive arterial pressure.

4.6. Clinical Implications and Recommendations:

1. **Prioritize Mechanical CPR for Remote Transport:** EMS systems operating in remote areas with prolonged transport times should strongly consider equipping vehicles with mechanical CPR devices like LUCAS as a standard of care. The demonstrated benefit in maintaining quality under duress outweighs concerns about deployment time in these contexts.

2. **Training and Deployment Protocols:** Focus training on rapid and reliable LUCAS deployment under various constraints (space, cold weather gloves). Develop clear protocols for when to deploy during transport (e.g., upon encountering rough terrain, for anticipated long transports, or if manual quality is observed to degrade).
3. **Vehicle Considerations:** Ambulance services for remote areas should prioritize vehicle stability (suspension), space optimization, and climate control to minimize environmental stressors, recognizing that even with mechanical CPR, rescuer comfort and ability to perform other tasks are enhanced.
4. **Utilize Monitoring:** Monitor CPR quality (via feedback devices if possible) and physiological parameters (EtCO2, ECG, invasive BP if feasible) closely during transport, regardless of method, to guide interventions.
5. **Research:** Field studies validating these simulation findings are needed. Research should also explore optimizing mechanical CPR deployment workflows in remote settings and the impact on long-term survival outcomes.

5. CONCLUSION

Environmental disturbances during patient transport in remote areas pose a formidable challenge to the delivery of high-quality manual CPR. This study unequivocally demonstrates that vibration, acceleration, spatial constraints, temperature extremes, and altitude significantly degrade manual compression metrics, induce hemodynamic instability (simulated BP fluctuations), and increase ECG artifact, compromising the resuscitation effort. In stark contrast, the LUCAS mechanical CPR device consistently delivered guideline-compliant compressions, maintained stable simulated hemodynamics, and provided clear ECG signals across all tested environmental extremes. Quantitative environmental exposure indices proved valuable tools for objectively characterizing stressors and predicting CPR degradation. For EMS systems serving remote populations, where transport times are long and environmental conditions are harsh, equipping vehicles with mechanical CPR devices like LUCAS is not merely an option but a critical investment in improving the quality of resuscitation care and, ultimately, the chances of survival from out-of-hospital cardiac arrest. The consistency and resilience offered by mechanical CPR under duress provide a vital advantage that manual efforts cannot match in these demanding contexts.

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