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Article

Thoracic Injury in Chest Compression: A Meta-Analysis and Preclinical Evaluation of a Self-Developed Flexible Wearable Assist Device

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Abstract: To systematically evaluate the difference in thoracic injury risk between mechanical and manual chest compressions in adults with cardiac arrest, and to preliminarily observe the trend of soft-tissue and visceral organ injury associated with a flexible liquid silicone-based wearable chest compression assist device in a porcine ventricular fibrillation model. In accordance with the PRISMA 2020 guidelines, PubMed, Embase, and the Cochrane Library were systematically searched from inception to June 20, 2026. Literature screening and data extraction were performed independently by two reviewers; a random-effects model was employed for meta-analysis. Concurrently, eight Bama miniature pigs were randomized into a manual chest compression group (n=4) and a flexible wearable chest compression assist device group (n=4). A ventricular fibrillation-induced cardiac arrest model was established, and injury severity was scored using a modified Post-Resuscitation Damage Assessment (PRDA) scale. Intergroup comparisons were subjected to descriptive trend analysis only. A total of 12 independent studies enrolling 3,546 patients were included in the meta-analysis. The overall incidence of compression-related injury was significantly higher in the mechanical chest compression group than in the manual group, with a pooled odds ratio (OR) of 2.36 (95% confidence interval [CI]: 1.09--5.09), an absolute risk increase of 12.58%, and a number needed to harm (NNH) of 8 (95% CI: 6--64). For secondary outcomes, an elevated risk of rib fracture was observed in the mechanical group (pooled OR 2.13, 95% CI: 1.41--3.23; absolute risk increase 16.56%), as was an elevated risk of hemothorax (pooled OR 2.25, 95% CI: 1.29--3.93; absolute risk increase 7.02%). In the animal experiment, the overall injury scores were comparable between the two groups (manual group 3.50 ±1.29 versus device group 3.75 ±0.96); neither pneumothorax, rib fracture, nor sternal fracture was observed in either group. The incidence of focal skin injury was higher in the device group (50%) than in the manual group (25%). The median scores for hemothorax and bronchial hemorrhage were slightly higher in the device group, whereas gastric hemorrhage was lower. Commercially available rigid mechanical chest compression confers a higher risk of thoracic injury than manual compression; individualized risk-benefit assessment is warranted in clinical practice. No significant amplification of severe injury risk was observed with the self-developed flexible device; however, its biomechanical safety advantages remain to be further validated in large-sample animal models with osteoporotic characteristics and subsequent preclinical studies.

Keywords: Cardiopulmonary resuscitation; Mechanical chest compression; Thoracic injury; Meta-analysis; Animal experiment; Flexible wearable chest compression assist device

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1. Introduction

High-quality chest compression is recognized as a central element in the effective delivery of cardiopulmonary resuscitation (CPR) [1]. Mechanical chest compression devices were developed to maintain stable compression depth, rate, and chest wall recoil

during prolonged resuscitation, and to attenuate compression quality deterioration attributable to rescuer fatigue. Mechanical CPR devices currently used in clinical practice primarily comprise piston-based systems (e.g., LUCAS) and load-distributing band (LDB) systems (e.g., AutoPulse). Although theoretical advantages in hemodynamic maintenance are offered by these devices, biomechanical safety concerns arising from their rigid mechanical interfaces remain a subject of shared interest in clinical and forensic medicine [2]. A higher incidence of thoracic skeletal injury has been suggested by existing epidemiological and autopsy studies to be associated with mechanical chest compression: substantial kinetic energy is concentrated at the focal sternal contact point by piston-based devices, predisposing to stress concentration effects; compressive force is distributed along the thoracic circumference by LDB systems, yet the biomechanical loading vectors of the ribs may be altered.

Although commercially available large-scale rigid mechanical chest compression devices confer certain advantages in hemodynamic maintenance, the attendant risk of thoracic injury associated with their stress-concentrating design constitutes a clinically significant problem that cannot be disregarded. To address the safety limitations of existing compression devices, our team independently developed a novel wearable chest compression assist device featuring a flexible liquid silicone-based cushioning substrate with integrated audio-visual feedback [3]. The present study was designed to characterize the injury profile of current rigid devices through meta-analysis, and to preliminarily explore a feasible pathway for injury risk reduction via an animal experiment. The following objectives were established: (1) to conduct an updated systematic review and meta-analysis to quantify the difference in injury risk between commercially available rigid mechanical chest compression and manual chest compression; and (2) to perform a controlled experiment using a Bama miniature pig ventricular fibrillation model to preliminarily observe the trend of severe injury risk associated with our self-developed flexible wearable chest compression assist device, thereby providing a reference framework for the subsequent clinical translation of low-injury compression devices.

2. Materials and Methods

2.1. Systematic Review and Meta-Analysis

2.1.1. Search Strategy and Eligibility Criteria

PubMed, Embase, and the Cochrane Library were systematically searched from inception to June 20, 2026. The search strategy was peer-reviewed in accordance with the PRESS (Peer Review of Electronic Search Strategies) checklist. The PubMed search strategy was constructed as follows: (((((((((heart Arrest[MeSH Terms]) OR (cardiac arrest[MeSH Terms])) OR (CPR[MeSH Terms])) OR (cardiopulmonary Resuscitation[MeSH Terms])) OR (heart Arrest[Title/Abstract])) OR (cardiac arrest[Title/Abstract])) OR (CPR[Title/Abstract])) OR (cardiopulmonary Resuscitation[Title/Abstract])) AND ((((((((((chest compression[MeSH Terms]) OR (LUCAS[MeSH Terms])) OR (LDB[MeSH Terms])) OR (AutoPulse[MeSH Terms])) OR (Load-distributing[MeSH Terms])) OR (chest compression[Title/Abstract])) OR (LUCAS[Title/Abstract])) OR (LDB[Title/Abstract])) OR (AutoPulse[Title/Abstract])) OR (Load-distributing[Title/Abstract]))) AND ((((((((((((safety[MeSH Terms]) OR (injury[MeSH Terms])) OR (damage[MeSH Terms])) OR (lesion[MeSH Terms])) OR (wound[MeSH Terms])) OR (fracture[MeSH Terms])) OR (hemorrhage[MeSH Terms])) OR (safety[Title/Abstract])) OR (injury[Title/Abstract])) OR (damage[Title/Abstract])) OR (lesion[Title/Abstract])) OR (wound[Title/Abstract])) OR (fracture[Title/Abstract])) OR (hemorrhage[Title/Abstract])).

Eligibility criteria were formulated based on the PICO (Population, Intervention, Comparison, Outcome) framework. Population (P): adult patients aged ≥18 years with non-traumatic cardiac arrest. Intervention (I): mechanical chest compression devices approved by the U.S. Food and Drug Administration (FDA) or bearing Conformité Européenne (CE) certification (LUCAS, AutoPulse, or equivalent devices). Comparison

(C): manual chest compression. Outcome (O): compression-related injuries; the primary outcome was the overall incidence of CPR-related injury, and secondary outcomes included rib fracture and pulmonary injury (hemothorax). Study design (S): published original comparative studies in English, including randomized controlled trials (RCTs), prospective cohort studies, retrospective cohort studies, or case-control studies. Systematic reviews, meta-analyses, narrative reviews, conference abstracts with incomplete data, editorials, correspondence, animal experiments, and studies enrolling exclusively pediatric populations were excluded. Literature screening was performed independently by two reviewers; disagreements were resolved through discussion and consensus.

2.1.2. Data Extraction and Quality Assessment

Study characteristics, sample sizes, device types, CPR durations, injury verification methods, and event counts were extracted independently by two reviewers. Randomized controlled trials were assessed using the Cochrane Risk of Bias 2 (RoB 2) tool; non-randomized studies were evaluated using the Newcastle-Ottawa Scale (NOS) (≥7 points indicating high quality, 4--6 points moderate quality, and <4 points low quality).

2.1.3. Statistical Analysis

Statistical analyses were performed using R software (version 4.3.2), with the meta and metafor packages. Dichotomous outcomes were expressed as odds ratios (ORs) with 95% confidence intervals (CIs). The primary analysis was conducted using a Mantel-Haenszel (M-H) random-effects model. Heterogeneity was assessed using the I^2 statistic and Cochran's Q test (25%, 50%, and 75% representing low, moderate, and high heterogeneity, respectively). Publication bias was evaluated using funnel plots and Egger's test ($P < 0.10$ indicating the presence of publication bias); a two-tailed $P < 0.05$ was considered statistically significant for all other tests.

2.2. Exploratory Comparative Animal Experiment in a Porcine Model

Chest compressions in the device group were performed using the novel wearable device (Figure 1), the calibration accuracy and compression adequacy of which have been validated and published previously. The device was secured to the rescuer's hand via a liquid silicone wrist strap with hook-and-loop fastening; the base was fabricated from liquid silicone material and integrated a pressure sensor, a high-precision accelerometer, and a liquid crystal display, providing real-time audio-visual feedback. The device remained powered on throughout the experiment; when a single compression deviated from the target range in depth or rate, corresponding alerts were generated to prompt the rescuer.

Figure 1. Appearance of the Self-Developed Flexible Wearable Chest Compression Assist Device Featuring a Liquid Silicone-Based Cushioning Substrate and Integrated Audio-Visual Feedback System.

1) Experimental animals: Eight Bama miniature pigs (aged 5--6 months, weighing 25--35 kg; Chongqing Jusha Biotechnology Co., Ltd.) were used. Ethical approval number: CQJS-EAER-2024-0006. 2) Model establishment: Anesthesia was induced with propofol, followed by endotracheal intubation and mechanical ventilation. Ventricular fibrillation was induced using a modified transcutaneous electrical stimulation method (27 V direct current, delivered for 3--8 s). Following confirmation, a no-intervention interval of 12 min was observed to simulate a delayed resuscitation scenario in the out-of-hospital setting[4]. 3) Grouping and intervention: The animals were randomized (1:1) into a manual chest compression group (n=4) and a flexible wearable chest compression assist device group (n=4). Both groups received compressions at a rate of 100--120 compressions/min and a depth of 5--6 cm; the device group wore the novel real-time feedback device with a liquid silicone substrate (Shore hardness ≤30A). At minute 18, biphasic defibrillation at 200 J was delivered. Animals that did not achieve return of spontaneous circulation within 30 min were euthanized. 4) Outcome assessment: Immediately postmortem, chest computed tomography (CT) and three-dimensional skeletal reconstruction were performed. Necropsy was conducted by a veterinary pathologist, and injury severity was scored using a modified Post-Resuscitation Damage Assessment (PRDA) scale [5]. Total scores were expressed as mean ± standard deviation; other variables were expressed as median (P25, P75). Cutaneous histology was qualitatively scored by a pathologist (0 = absent, 1 = present). Given the exploratory nature of this animal experiment and the limited sample size, statistical power was insufficient; therefore, the results were subjected to descriptive trend analysis only.

3. Results

3.1. Systematic Review and Meta-Analysis

3.1.1. Literature Screening and Characteristics of Included Studies

A total of 1,358 records were retrieved from PubMed, Embase, and the Cochrane Library. Following duplicate removal by software and manual verification (n = 332), 1,026 records remained for title/abstract screening, from which 497 records (animal experiments and pediatric studies) were excluded. Five hundred twenty-nine articles underwent full-text review; 515 were excluded for topic mismatch, document type mismatch, or study design mismatch. Of the remaining 14 articles, 2 were excluded due to unavailable outcome data. Ultimately, 12 independent studies were deemed eligible and were included in the quantitative synthesis (Figure 2, PRISMA flow diagram).

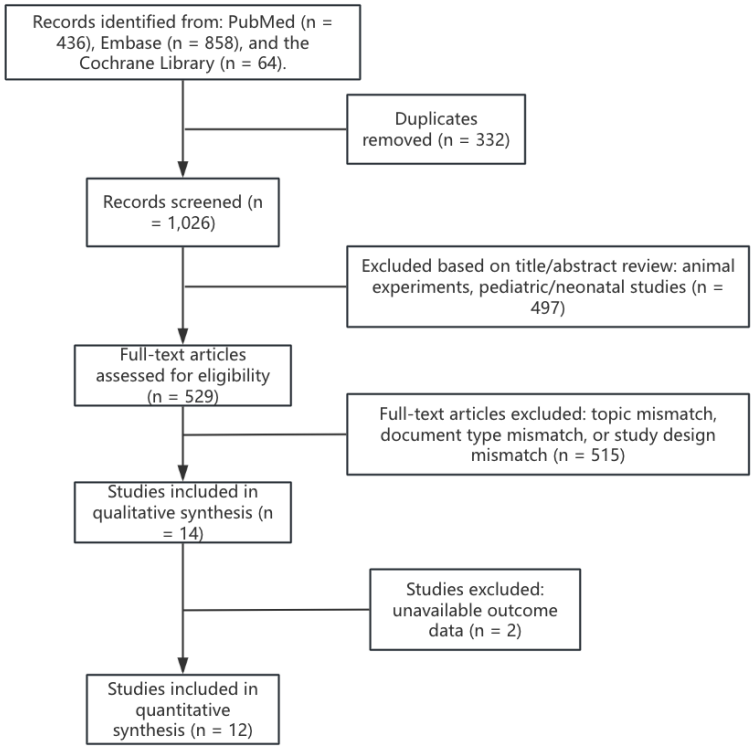

Figure 2. PRISMA 2020 flow diagram of study selection process.

The 12 included studies comprised 3,546 patients (1,309 in the mechanical chest compression group and 2,237 in the manual chest compression group) [6–17]. Publication dates ranged from 2009 to 2026, with studies conducted across nine countries (Sweden, the United States, Germany, Switzerland, the Netherlands, Denmark, the Czech Republic, Israel, and Turkey). Regarding study design, seven were retrospective cohort studies, three were prospective cohort studies, one was a prospective multicenter study, and one was a randomized controlled trial. Injury assessment methods comprised forensic autopsy alone (seven studies), postmortem computed tomography (PMCT) alone (two studies), and a combination of autopsy, PMCT, and clinical imaging (three studies). The mechanical device was predominantly LUCAS (piston-type) in ten studies; mixed devices or AutoPulse (LDB-type) were used in two studies. The baseline characteristics of the included studies are presented in Table 1.

Table 1. Baseline Characteristics of the 12 Included Studies

Study (Year)	Study Design	Country	Device Type	Mechanical Group, n	Manual Group, n	Injury Assessment Method	NOS Score / RoB 2
Karasek (2021)	Retrospective multicenter autopsy study	Czech Republic	LUCAS II / AutoPulse	64	559	Forensic autopsy (AIS/NISS scoring)	5
Ondruschka (2018)	Retrospective single-center autopsy study	Germany	LUCAS II	113	501	Forensic autopsy	5

Friberg (2019)	Prospective autopsy study	Sweden	LUCAS 1/2	362	52	Standardized autopsy (soft-tissue injury grading)	6
Smekal (2014)	Prospective multicenter autopsy study	Sweden	LUCAS	139	83	Standardized autopsy protocol	6
Smekal (2009)	Prospective dual-center autopsy study	Sweden	LUCAS	38	47	Standardized autopsy protocol	5
Turan (2026)	Retrospective cohort study	Turkey	LUCAS 2	50	66	Chest CT within 6 h post-resuscitation	5
Saleem (2022)	Retrospective cohort study	Israel	LUCAS	62	45	Chest radiography + bedside ultrasonography	5
Pinto (2013)	Retrospective autopsy study	United States	AutoPulse	88	87	Forensic autopsy	5
Baumeister (2015)	Retrospective autopsy-imaging study	Switzerland	LUCAS 2	24	20	Postmortem CT (PMCT)	4
Koster (2017)	Prospective RCT (non-inferiority)	Netherlands	AutoPulse / LUCAS	237	137	PMCT / autopsy / clinical follow-up	Cochrane RoB 2
Milling (2019)	Retrospective cohort study	Denmark	LUCAS	84	353	Medical record review + autopsy	5
Preda (2023)	Retrospective cohort study	Switzerland	Mechanical CPR (device type unspecified)	48	287	ICU clinical assessment + imaging	5

3.1.2. Quality Assessment

Among the 11 non-randomized studies, none was rated as high quality (NOS ≥7); all were classified as moderate quality (NOS 4--6), with two studies scoring 6 points, eight studies scoring 5 points, and one study scoring 4 points. The most common methodological limitations were failure to control for CPR duration (seven studies) and the exclusive inclusion of deceased patients in autopsy studies (eight studies), introducing a risk of selection bias. The sole randomized trial was judged as raising "some concerns" in RoB 2, primarily attributable to its open-label design and the use of mixed sources for outcome assessment (autopsy plus clinical follow-up).

3.1.3. Primary Outcome: Overall CPR-related Injury

Data on the primary outcome-the overall incidence of compression-related injury-were extractable from six studies for pooled analysis. A random-effects model was applied. Substantial heterogeneity was observed (I^2 = 80.2%), and the overall effect test yielded Z = 2.18, P = 0.029. The pooled effect estimate was an OR of 2.36 (95% CI: 1.09--5.09), which was statistically significant. The absolute risk increase was 12.58%, with an event rate of 75.06% in the control group and 87.64% in the experimental group; the number needed to harm (NNH) was 8 (95% CI: 6--64).

As shown in the forest plot (Figure 3), the 95% confidence intervals for Friberg, Ondruschka, and Smekal lay entirely to the right of the line of no effect, whereas the confidence intervals of the remaining three studies crossed the null line. The 95% confidence interval of the pooled effect (1.09--5.09) excluded 1.0, indicating a higher overall injury risk with mechanical chest compression than with manual chest compression.

In the sensitivity analysis, the pooled OR fluctuated between 1.81 and 3.07 when individual studies were sequentially omitted (full model: 2.36). The direction or statistical significance of the pooled effect was altered upon exclusion of Smekal, Ondruschka, or Friberg, suggesting that these four studies exerted a substantial influence on the pooled estimate.

The overall certainty of evidence was rated as low (LOW; score 2/4) according to the GRADE framework, downgraded by two levels for inconsistency (I^2 = 80.2%, Cochran's Q test P < 0.001). No serious concerns regarding risk of bias, indirectness, or imprecision were identified. Formal downgrade for publication bias was not applied because fewer than 10 studies were included, rendering the test for publication bias underpowered.

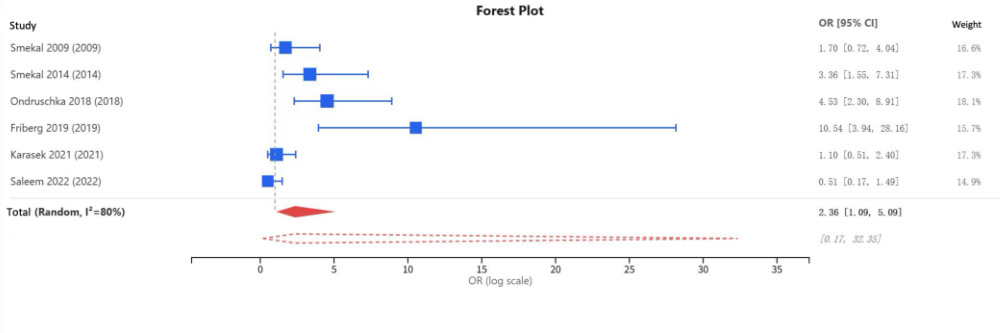

Figure 3. Forest plot of the overall incidence of compression-related injury.

3.1.4. Secondary Outcomes: Skeletal Injury and Hemothorax

Data on the secondary outcome of overall rib fracture incidence were extractable from eight studies for pooled analysis. A random-effects model was applied. Moderate heterogeneity was observed (I^2 = 56.4%), and the overall effect test yielded Z = 3.56, P < 0.001. The pooled effect estimate was an OR of 2.13 (95% CI: 1.41--3.23), which was statistically significant. The absolute risk increase was 16.56%, and the number needed to harm (NNH) was 7 (95% CI: 5--13).

As shown in the forest plot (Figure 4), Friberg demonstrated the largest effect size with a confidence interval distant from the line of no effect; the 95% confidence intervals for Ondruschka, Milling, and Smekal lay entirely to the right of the null line; the confidence intervals of the remaining four studies crossed the line of no effect. The 95% confidence interval of the pooled effect (1.41--3.23) excluded 1.0, indicating a higher overall risk of rib fracture with mechanical chest compression than with manual chest compression.

In the sensitivity analysis, the pooled OR fluctuated between 1.93 and 2.34 when individual studies were sequentially omitted. Upon exclusion of Friberg, the pooled OR decreased to 1.93 (95% CI: 1.48--2.52), with a marked reduction in heterogeneity (I^2 = 3.4%).

Influence diagnostics revealed that Cook's D (0.7625) and the studentized residual (2.337) for Friberg exceeded conventional thresholds, flagging this study as potentially influential.

The certainty of evidence was rated as moderate (MODERATE; score 3/4) according to the GRADE framework, downgraded by one level for inconsistency (I^2 = 56.4%, Cochran's Q test P = 0.025).

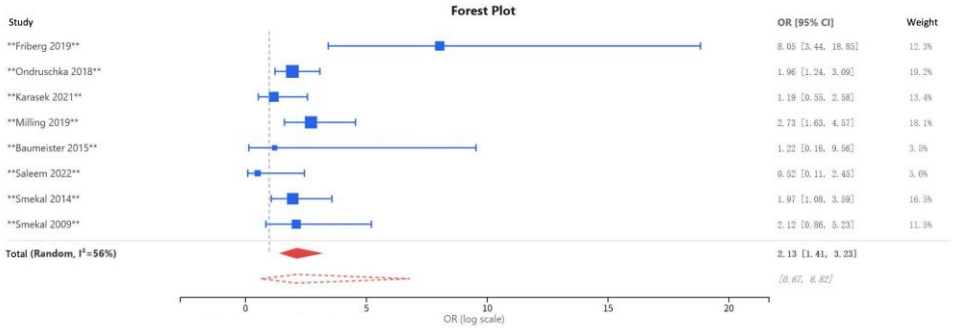

Figure 4. Forest plot of the overall incidence of rib fractures.

Data on the incidence of hemothorax were extractable from eight studies for pooled analysis. A random-effects model was applied. Heterogeneity was low to moderate (I^2 = 36.1%), and the overall effect test yielded Z = 2.86, P = 0.004. The pooled effect estimate was an OR of 2.25 (95% CI: 1.29--3.93), which was statistically significant. The absolute risk increase was 7.02%, and the number needed to harm (NNH) was 15 (95% CI: 7--58).

As shown in the forest plot (Figure 5), Ondruschka demonstrated the largest effect size with a confidence interval distant from the line of no effect; the effect estimates for Milling, Karasek, and Baumeister lay to the right of the null line, yet their confidence intervals crossed the line of no effect; the confidence intervals of the remaining four studies all crossed the null line. The 95% confidence interval of the pooled effect (1.29--3.93) excluded 1.0, indicating a higher risk of hemothorax with mechanical chest compression than with manual chest compression.

In the sensitivity analysis, the pooled OR fluctuated between 1.72 and 2.63 when individual studies were sequentially omitted. Upon exclusion of Ondruschka, the pooled OR decreased to 1.72 (95% CI: 1.12--2.64), with a marked reduction in heterogeneity (I^2 = 0%). Influence diagnostics revealed that Cook's D (0.7674) and the studentized residual (1.979) for Ondruschka exceeded conventional thresholds, flagging this study as potentially influential.

The certainty of evidence was rated as high (HIGH; score 4/4) according to the GRADE framework; no downgrade was applied because heterogeneity was low (I^2 = 36.1%, Cochran's Q test P = 0.141).

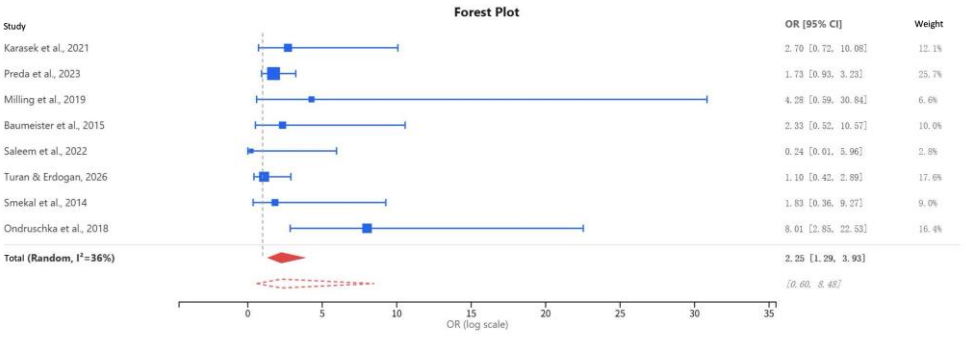

Figure 5. Forest plot of the incidence of hemothorax.

3.1.5. Sensitivity Analysis

In the leave-one-out analysis across the primary and secondary outcomes, the pooled OR for overall injury ranged from 1.81 to 3.07 (full model: 2.36), that for rib fracture ranged from 1.93 to 2.34 (full model: 2.13), and that for hemothorax ranged from 1.72 to 2.63 (full model: 2.25); all estimates remained statistically significant, indicating satisfactory robustness of the findings. Meta-regression with publication year as a covariate identified no significant temporal trend, suggesting that publication year did not exert a significant effect on the pooled estimates.

3.1.6. Publication Bias

For the three outcomes of overall injury, rib fracture, and hemothorax, the funnel plots (Figures 6--8) showed that the majority of studies were distributed in the non-significant region ($P \geq 0.10$), indicating limited evidence of publication bias driven by statistical significance. Trim-and-Fill analysis estimated the presence of 2, 4, and 3 missing studies for the three outcomes, respectively; the adjusted ORs were 3.11 (95% CI: 2.31--4.19), 2.38 (95% CI: 1.93--2.93), and 2.59 (95% CI: 1.89--3.55), all continuing to indicate a higher injury risk with mechanical CPR than with manual CPR.

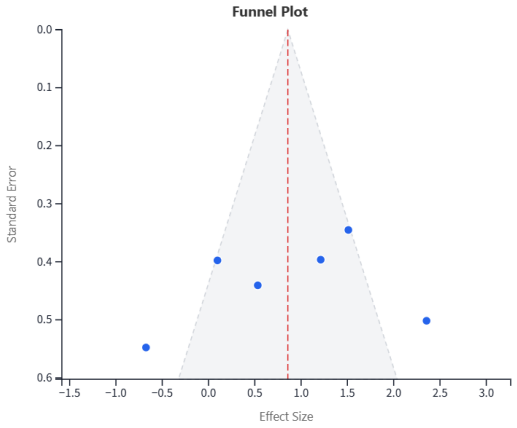

Figure 6. Funnel plot for publication bias assessment of the overall incidence of compression-related injury. The x-axis represents the log odds ratio (log[OR]), and the y-axis represents the standard error (SE); larger studies are positioned toward the upper portion. A mild rightward skew is observed, with scatter points slightly more numerous to the right of the pooled effect line than to the left. Dashed lines indicate the boundaries of the 95% pseudo-confidence interval.

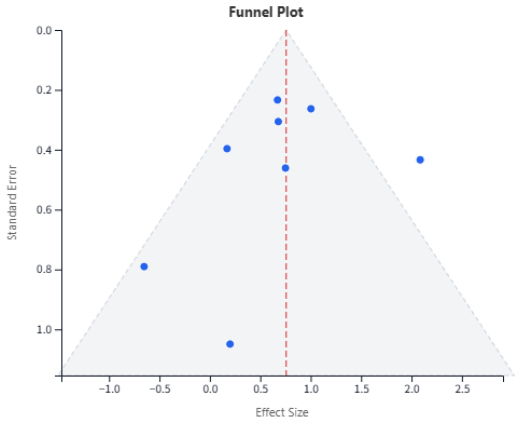

Figure 7. Funnel plot for publication bias assessment of the incidence of rib fractures.

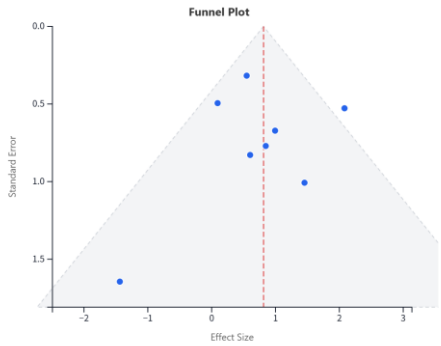

Figure 8. Funnel plot for publication bias assessment of the incidence of hemothorax.

3.2. Exploratory Comparative Animal Experiment in a Porcine Model

3.2.1. Assessment of Injury Scores

The overall injury score was 3.62 ± 1.06. The total score in the manual chest compression group was 3.50 ± 1.29, and that in the flexible wearable chest compression assist device group was 3.75 ± 0.96. Neither pneumothorax, rib fracture, nor sternal fracture occurred in either group (Figure 9). The incidence of focal skin injury was 25% in the manual group and 50% in the device group. Detailed scores are presented in Table 2.

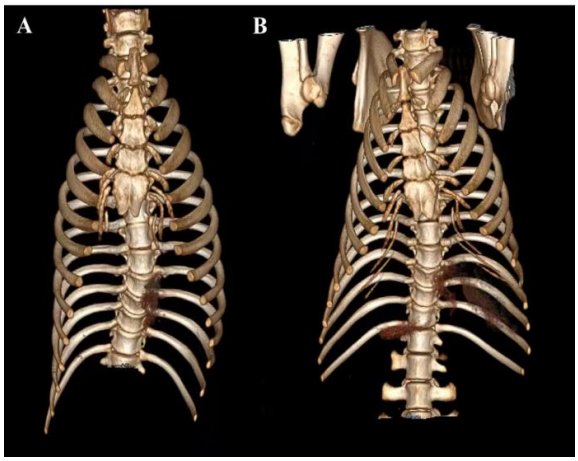

Figure 9. Three-dimensional Skeletal Reconstruction Images. (A) Manual Group; (B) Device Group.

Table 2. Post-Resuscitation Injury Scores in the Porcine Model

Variable	Overall (n = 8)	Manual Chest Compression Group (n = 4)	Flexible Wearable Chest Compression Assist Device Group (n = 4)
Total score, Mean ± SD	3.62 ± 1.06	3.50 ± 1.29	3.75 ± 0.96
Hemothorax, M (P25, P75)	2.00 (0.00, 2.00)	1.00 (0.00, 2.50)	2.00 (1.50, 2.00)
Pneumothorax, M (P25, P75)	0.00 (0.00, 0.00)	0.00 (0.00, 0.00)	0.00 (0.00, 0.00)
Rib fracture, M (P25, P75)	0.00 (0.00, 0.00)	0.00 (0.00, 0.00)	0.00 (0.00, 0.00)
Sternal fracture, M (P25, P75)	0.00 (0.00, 0.00)	0.00 (0.00, 0.00)	0.00 (0.00, 0.00)
Hemopericardium, M (P25, P75)	0.00 (0.00, 1.00)	0.00 (0.00, 1.00)	0.00 (0.00, 1.00)

Gastric hemorrhage, M (P25, P75)	0.00 (0.00, 1.00)	0.50 (0.00, 1.00)	0.00 (0.00, 0.25)
Bronchial hemorrhage, M (P25, P75)	0.75 (0.75, 1.00)	0.50 (0.00, 1.00)	1.00 (1.00, 1.00)
Skin injury status (0 = absent, 1 = present), n (%)			
0	5 (62.50)	3 (75.00)	2 (50.00)
1	3 (37.50)	1 (25.00)	2 (50.00)

3.2.2. Skin and Microscopic Pathology

The incidence of focal skin injury was 25% (1/4) in the manual chest compression group and 50% (2/4) in the flexible wearable chest compression assist device group. Histopathological sections stained with hematoxylin and eosin (H&E) preliminarily revealed no severe laceration of the underlying muscle layer in either group, and the degree of mild epidermal exfoliation was comparable between the two groups.

4. Discussion

4.1. Interpretation of Meta-Analysis Results

The results of the present meta-analysis demonstrated that, among adult patients with cardiac arrest, the risk of overall compression-related injury associated with commercially available rigid mechanical chest compression was approximately 2.36-fold higher than that with manual compression (OR 2.36, 95% CI: 1.09--5.09), corresponding to approximately one additional injury event per eight patients treated (NNH 8). This direction of effect was consistent with the conclusions of the majority of previous autopsy series and observational studies, suggesting that rigid mechanical devices are accompanied by a non-negligible biomechanical safety cost while maintaining hemodynamic efficacy through high stress concentration or redistribution of thoracic circumference loading. For the secondary outcomes, consistent upward trends were observed in the risks of rib fracture and hemothorax. The pooled OR for rib fracture was 2.13 (95% CI: 1.41--3.23), with an absolute risk increase of 16.56%, indicating that the stress loading on the thoracic skeletal structure by mechanical compression was significantly higher than that by manual compression; the pooled OR for hemothorax was 2.25 (95% CI: 1.29--3.93), with an absolute risk increase of 7.02%, demonstrating that mechanical compression not only increased bony injury but also could cause pulmonary parenchymal and vascular damage through laceration by fractured bone ends or abrupt alterations in intrathoracic pressure. Substantial heterogeneity was observed for the overall injury outcome (I^2 = 80.2%), driven primarily by two large-effect autopsy studies; both studies enrolled populations with out-of-hospital cardiac arrest and prolonged CPR duration, and carried substantial weight in the pooled analysis. Sensitivity analyses revealed that the statistical significance of the pooled effect estimate was lost or attenuated upon exclusion of these studies, suggesting that the injury risk of mechanical chest compression may be further amplified in specific high-risk populations (e.g., prolonged resuscitation, out-of-hospital settings).

Regarding the certainty of evidence, the overall injury outcome was rated as low quality by GRADE due to high heterogeneity, rib fracture as moderate quality, and hemothorax as high quality. It should be emphasized that only one included study was a randomized controlled trial, whereas the remainder employed observational designs; moreover, autopsy studies are inherently subject to selection bias (inclusion of deceased patients only). Therefore, although current evidence suggests an elevated injury risk with mechanical chest compression, it is insufficient to negate the value of mechanical devices in maintaining hemodynamics in specific scenarios (e.g., prehospital transport, catheter laboratory procedures). Clinical decision-making should entail a balanced weighing of the benefits of maintained compression quality against the increased risk of injury, rather than a categorical rejection of mechanical devices.

4.2. Animal Experiment as Biomechanical Mechanistic Corroboration

Although current resuscitation guidelines emphasize the minimization of no-flow time [18], animal tissues retain favorable compliance and viscoelasticity under brief ischemic conditions. This viscoelastic "protective barrier" delays the manifestation of visible injuries, thereby masking early potential microstructural damage[19]. Furthermore, in real-world out-of-hospital cardiac arrest scenarios-particularly in unwitnessed or remote-area cases-emergency response times often approach or exceed 10 minutes. In such refractory cases, ischemic fragility of the chest wall constitutes an objectively present pathological substrate [20], providing a degree of clinical translational relevance for the intervention protocol employed in the present study. Accordingly, the central consideration underlying the model design was the establishment of an approximately 12-minute no-flow interval (untreated ventricular fibrillation) with a delayed-defibrillation paradigm, thereby simulating clinically representative severe cardiac arrest beyond the resuscitation golden window [21]. Under prolonged systemic ischemia-hypoxia, tissue fragility and microvascular permeability increase precipitously [22]. The administration of guideline-recommended depth cardiopulmonary compressions during this phase of heightened physiological vulnerability was intended to maximally elicit and expose potential cumulative mechanical injury.

The overall injury scores indicated that the two groups were essentially comparable in numerical magnitude. Although constrained by the small sample size (n = 8) and the objective factor of higher thoracic compliance in healthy animals, these findings are insufficient to establish clinical equivalence; however, as an exploratory safety threshold test, no significant amplification of severe injury risk was observed.

Regarding visceral microcirculatory hemorrhage indicators, the median hemothorax score (2.0) and median bronchial hemorrhage score (1.00) in the device group were slightly higher than those in the manual chest compression group (hemothorax 1.00, bronchial hemorrhage 0.50). From a biofluid-mechanical perspective, this mild trend toward respiratory tract and pleural cavity oozing may conversely suggest the compression efficacy of the device group. Manual compression is highly susceptible to depth and force attenuation attributable to rescuer fatigue, whereas device assistance may sustain more prolonged and deeper effective thoracic compression, thereby inducing blood extravasation. Notably, the median gastric hemorrhage score in the device group was lower than that in the manual group, which may suggest that the device effectively anchored the standard compression anatomical position through its base design or wearing configuration, preventing caudal force deviation and conferring a protective effect on subdiaphragmatic viscera.

The potential reasons underlying the absence of a significant increase in severe fracture risk with this device may be related to its design characteristics. First, the real-time audio-visual feedback system provides a cognitive constraint mechanism for rescuers [23], preventing skeletal fracture due to loss of operational control by restricting excessively deep or shallow compressions. Second, the thoracic compliance of healthy young experimental pigs is markedly superior to that of elderly patients with osteoporosis commonly encountered in clinical practice; such an animal model is less prone to inducing compression fractures frequently observed clinically. Therefore, the negative fracture findings in this animal experiment should be interpreted with caution.

At the microscopic and soft-tissue level, the incidence of focal skin injury in the flexible wearable chest compression assist device group (50%, 2/4) was higher than that in the manual group (25%, 1/4). In conjunction with the histopathological findings that no severe laceration of the underlying muscle layer was observed in either group and that the degree of epidermal exfoliation was comparable, this increased superficial skin injury may be attributable to the physical surface properties of the device material. This suggests that future product iterations should prioritize the optimization of skin-friendly properties and the friction coefficient of the substrate material.

4.3. Clinical Implications

First, the selection of chest compression devices should be individualized based on patient anatomical characteristics and anticipated resuscitation duration. In patients with fragile anterior chest walls, load-distributing band devices may confer an advantage in sternal protection; in patients with osteoporotic changes of the posterior ribs or spinal kyphosis, piston-type devices may be relatively more appropriate. No absolutely superior device currently exists; however, an anatomy-informed selection strategy may reduce injury risk to a certain extent.

Second, the present study preliminarily indicated the safety inadequacy of existing commercially available rigid mechanical chest compression devices through meta-analysis, and, in conjunction with clinical emergency requirements, a flexible wearable chest compression assist device was designed. Exploratory animal experiment results preliminarily demonstrated that, although numerically slightly higher injury values for skin and hemorrhage were observed in the device group, no trend toward amplified risk was observed for fractures or severe visceral injuries, demonstrating a certain biomechanical application reference direction. The wearable characteristics and relatively simple operational requirements of this device render it potentially applicable in resource-limited prehospital emergency settings or primary medical institutions, as an auxiliary tool for improving compression quality compliance.

4.4. Limitations

The present study is subject to several limitations. First, observational studies constituted the absolute majority in the meta-analysis; only one randomized controlled trial (Koster 2017) met the stringent eligibility criteria, and the pooled effect estimates may be influenced by residual confounding. Second, autopsy studies predominantly enrolled non-survivors, introducing a potential risk of selection bias: deceased patients may have sustained more severe injuries or undergone longer CPR duration, leading to overestimation of injury rates in both groups; conversely, survivors with less severe injuries were systematically excluded from injury assessment, potentially resulting in underestimation of the true incidence of injury. Third, substantial heterogeneity was observed for the primary outcome ($I^2 = 80.2\%$), reflecting genuine clinical diversity across studies in device type, CPR duration, patient population, and injury definition. Fourth, the present study combined meta-analysis with an exploratory comparative animal experiment in a porcine model; however, the objective limitations inherent to both designs must be acknowledged. The meta-analysis included clinically predominant large-scale rigid mechanical chest compression devices (LUCAS, AutoPulse), whereas the animal experiment employed a flexible wearable chest compression assist device. Moreover, the thoracic compliance of healthy young experimental pigs is markedly superior to that of elderly patients with osteoporosis commonly encountered in clinical practice. These objectively present differences in device material composition and species limitations explain why severe rib or sternal fractures-frequently reported in the meta-analysis-were absent in the animal experiment. Fifth, the exploratory comparative animal experiment enrolled only eight experimental pigs, representing an extremely small sample size with insufficient statistical power; the observed injury findings can provide only preliminary phenomenological reference from pathological and biomechanical perspectives, with limited extrapolative value. Future validation in larger samples and large-animal models with osteoporotic characteristics is warranted. Finally, because the model was designed with prolonged ischemic characteristics, hemodynamic parameters and neurological functional outcomes were not incorporated into the assessment framework.

5. Conclusions

Commercially available rigid mechanical chest compression confers a higher risk of thoracic injury than manual compression; individualized risk-benefit assessment is warranted in clinical practice. No significant amplification of severe injury risk was observed with the self-developed flexible device; however, its biomechanical safety

advantages remain to be further validated in large-sample animal models with osteoporotic characteristics and subsequent preclinical studies.

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