Risk Factors for Lower Extremity Injuries across Injury Severity among Cab-over-engine Light Truck Occupants in Road Traffic

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Abstract This study aimed to identify independent risk factors for lower extremity (LE) injuries by anatomical subregion among cab-over-engine (COE) light truck occupants involved in road traffic accidents.

A retrospective analysis was conducted using Korean In-Depth Accident Study (KIDAS) data from 2011 to 2024. After excluding occupants aged <15 years or with unclear injury or collision data, 462 cases were analysed. LE injuries were categorised into five subregions: pelvis, femur, knee, lower leg, and foot. Logistic regression identified independent predictors of injury by subregion, stratified by injury severity (ISS <16 and ≥16).

Severe vehicle deformation (crush extent ≥6) was the strongest predictor of overall LE injury. Frontal airbag deployment was independently associated with overall LE, pelvis, and foot injuries. Seatbelt use was protective against overall LE injury. Left-side impact was associated with overall LE injury and, among severely injured occupants, with pelvis injury. Among severely injured occupants, airbag deployment was significantly associated with foot injury.

These findings suggest that the structural characteristics of COE light trucks may increase lower extremity exposure during high-energy frontal collisions, particularly in association with severe vehicle deformation and frontal airbag deployment. These results may inform future research on structural and restraint design strategies specific to COE vehicles.

Keywords Cab-over-engine light truck, Injury, Lower extremity, Occupant, Risk factor

I. INTRODUCTION

Road traffic injuries remain a leading cause of death and disability worldwide, imposing a substantial disease burden particularly among children, adolescents, and young adults. According to the World Health Organization's Global Status Report on Road Safety 2023, approximately 1.19 million deaths occur annually due to road traffic crashes [1], and road traffic injuries are reported as a leading cause of death among individuals aged 5–29 years [2]. Given that survivors frequently face long-term functional impairment and considerable socioeconomic consequences, effective prevention and injury mitigation strategies are essential.

Crashes involving large vehicles are associated with an elevated risk of serious injury, attributable to mass disparity, energy transfer characteristics, and greater structural rigidity compared to passenger vehicles. In the United States, 4,761 fatalities were recorded in crashes involving large trucks among 37,133 total traffic fatalities in 2017, underscoring the public health significance of truck-related collisions [3]. Identifying the factors that contribute to serious injury in truck occupants and occupants of opposing vehicles is therefore critical for informing crashworthiness design and prehospital triage strategies [4].

Among truck configurations, cab-over-engine (COE) light trucks have a markedly shorter front crush zone compared to conventional bonnet-type trucks, which may limit energy-absorption capacity during frontal impacts and increasing the risk of occupant compartment deformation and intrusion. Jeon et al. demonstrated that occupants of cab-over-type trucks involved in frontal crashes had a significantly higher risk of serious lower extremity injury than occupants of non-cab-over vehicles, attributing this difference to the shortened front crush zone and the proximity of the cab to the point of impact [5]. These findings provide a biomechanical and epidemiologic rationale for vehicle-type-specific analysis of lower extremity injuries in COE light trucks. Although previous studies have examined injury outcomes in truck-related crashes and the biomechanics of lower extremity injuries in frontal impacts [6,7], evidence specifically addressing COE light trucks remains limited. This vehicle type therefore has a distinct structural profile that may be associated with lower extremity injury patterns not fully captured by studies of heavy trucks or conventional bonnet-type vehicles. Lower extremity injuries are less immediately life-threatening than injuries to vital structures, but they are a major source of long-term functional impairment and rehabilitation costs, accounting for a substantial proportion of traffic injury-related

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economic burden [8]. COE light trucks are widely operated in Korea and across Asia due to their suitability for narrow road environments and high cargo efficiency [5]. Although the COE configuration is largely dictated by operational requirements and infrastructure, its shortened front crush zone and limited energy-absorption space may create distinct lower extremity injury mechanisms during crashes. Therefore, identifying injury patterns according to crash condition, injury severity, and anatomical subsite is important for informing future evaluation of COE-specific frontal structural design, restraint-system performance, and prehospital triage strategies.

Lower extremity injuries are frequently observed in frontal crashes and encompass distinct injury mechanisms depending on the anatomical subsite. The knee–thigh–hip complex is primarily subjected to flexion and shear loading from dashboard contact, whereas the lower leg and foot/ankle region are more heavily influenced by footwell intrusion and deformation of pedal and floor structures [7,9]. Evaluating lower extremity injury solely in terms of overall presence or severity may therefore obscure clinically and biomechanically important relationships between intrusion, load transfer, and subsite-specific injury patterns.

Although previous studies have examined injury outcomes in truck-related crashes and the biomechanics of lower extremity injuries in frontal impacts [6,7], evidence specifically addressing COE light trucks remains limited. This vehicle type therefore has a distinct structural profile that may be associated with lower extremity injury patterns not fully captured by studies of heavy trucks or conventional bonnet-type vehicles. In the context of prehospital care, rapid clinical decision-making is essential because COE light truck occupants involved in high-energy crashes may have multiple concurrent injuries, occult lower extremity trauma, or vascular compromise requiring timely triage, appropriate transport destination selection, and early trauma resource activation. Evidence addressing which anatomical subsites are at greatest risk under specific crash conditions therefore carries both clinical and engineering value.The present study therefore utilized data from the Korean In-Depth Accident Study (KIDAS) [10,11], to describe the anatomical distribution of lower extremity injuries among COE light truck occupants involved in road traffic crashes. We further aimed to identify factors independently associated with injury at each anatomical subsite and to examine how these risk factors differ according to overall injury severity.

II. METHODS

This was a retrospective observational study using data from the Korean In-Depth Accident Study (KIDAS) database. KIDAS is a multi-institutional crash injury surveillance database in which medical personnel and trained investigators systematically collect data on occupant characteristics, injury information, crash-related vehicle factors, road and environmental conditions, and vehicle damage. KIDAS is not based on random sampling of all road traffic crashes in Korea. Rather, it is based on motor vehicle crash occupants who visited participating emergency medical centers with injury or suspected injury after a crash. Therefore, the database includes occupants across a range of injury severities among those captured at participating institutions, but does not include all crashes, such as property-damage-only crashes or crashes involving occupants who did not seek care at participating hospitals. Accordingly, KIDAS should not be considered fully representative of the entire Korean crash population. Occupants without lower extremity injuries in this study were not necessarily uninjured and may have sustained injuries to other body regions. The study period was from January 1, 2011 to December 31, 2024. Ethical approval was obtained from the Institutional Review Board of Wonju Severance Christian Hospital (approval number: CR323010), and informed consent was waived given the retrospective nature of the study.

The study population comprised occupants of COE light trucks recorded in the KIDAS database during the study period. Occupant type (driver or passenger) and seating position were classified based on KIDAS records. The following exclusion criteria were applied: (1) missing or swipe-coded Collision Deformation Classification (CDC) data, with swipe-coded data defined as sideswipe-type or glancing deformation patterns that precluded reliable identification of a single principal direction of force or representative deformation extent; (2) non-COE light truck occupants; (3) age younger than 15 years; (4) missing AIS codes required for lower extremity injury classification; and (5) multiple-impact crashes, defined as cases with two or more distinct CDC codes in a single crash event, as these preclude reliable classification of a single principal direction of force. A total of 462 occupants were included in the final analysis.

Vehicle damage was standardized using the Collision Deformation Classification (CDC) code [12]. The CDC system, developed by the Society of Automotive Engineers (SAE), encodes the location, type, and extent of vehicle deformation using a seven-character alphanumeric code. In this study, the directional and locational information within the CDC code was used to estimate the Principal Direction of Force (PDOF) and to categorize crash type. Crash types were classified as frontal, left-side, right-side, rear-end, and rollover. Rollover was defined by the presence of the code 'O' in the deformation type field of the CDC code. Crash severity was approximated using the CDC deformation extent, categorised as minor (extent 1–2), moderate (extent 3–5), and severe (extent ≥6). Delta-V was available for a subset of cases and was reported descriptively; however, it was not included as a predictor in the multivariable models because of a high proportion of missing values, approximately 60%, which would have substantially reduced the analytic sample and potentially introduced selection bias. Overlap was not available as a separately coded variable in the KIDAS database. Therefore, CDC deformation extent was used as a surrogate measure of crash severity and vehicle deformation.

Seatbelt use and frontal airbag deployment were included as restraint-related variables. Side airbag and knee airbag deployment were not included in the regression models because these systems were not equipped in the COE light trucks included in this study.

Injury information in KIDAS was obtained from linked hospital medical records at participating institutions rather than from post-crash follow-up surveys. Trained investigators systematically reviewed emergency department records, inpatient records, radiology reports, and operative records to collect detailed injury information. These trained investigators included dedicated AIS coordinators working at trauma centers. Injury coding was performed using the Abbreviated Injury Scale (AIS) 2008 revision [13]. The AIS, developed by the Association for the Advancement of Automotive Medicine (AAAM), provides a standardized anatomical framework for characterizing injury location and severity. Lower extremity injuries were classified by anatomical subsite — pelvis, femur/thigh, knee/patella, lower leg (tibia and fibula), and foot/ankle — based on AIS codes. Superficial injuries, including contusions, abrasions, and minor lacerations (i.e., external AIS codes of limited clinical or biomechanical significance), were excluded from the lower extremity injury definition. The maximum AIS at each subsite was calculated for each occupant. Overall injury severity was summarized using the Maximum Abbreviated Injury Score (MAIS). For stratified analyses, occupants were classified into non-severe (ISS <16) and severe (ISS ≥16) injury groups based on the Injury Severity Score (ISS) [14]. Age was categorised into three groups (15–39, 40–64, and ≥65 years) with reference to national administrative life-stage classifications and the distribution of the study sample [15].

Body mass index (BMI) was calculated as weight (kg) divided by height squared (m^2) and classified according to the Korean Society for the Study of Obesity criteria as underweight (<18.5 kg/m^2), normal (18.5–22.9 kg/m^2), overweight (23.0–24.9 kg/m^2), and obese (≥25.0 kg/m^2) [16]. Emergency department disposition was categorised as discharge, transfer, admission, or death. Concomitant injuries to other body regions were characterized using AIS-based data for descriptive purposes.

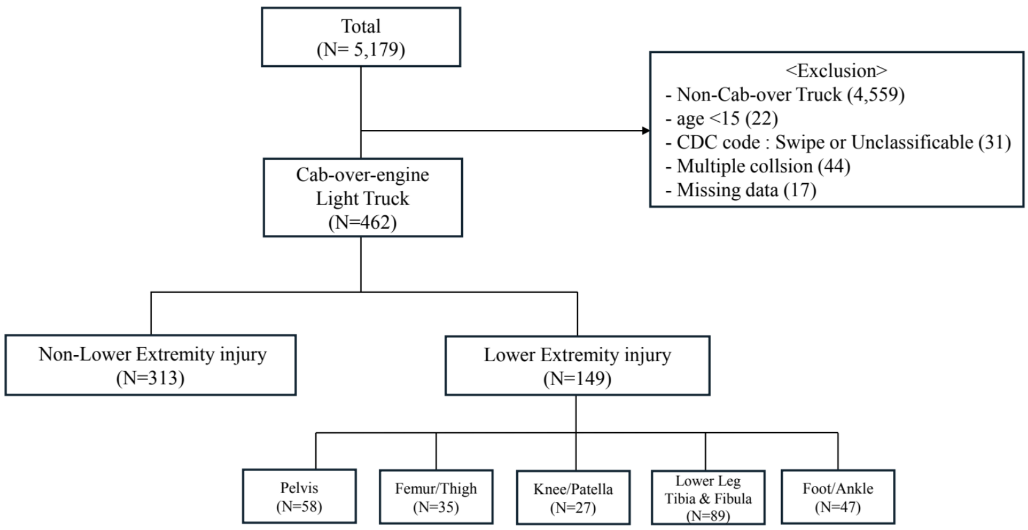

Fig. 1. Flow diagram of study participant selection from the Korean In-Depth Accident Study (KIDAS), 2011–2024. All counts refer to individual occupants.

All statistical analyses were performed using SAS Studio (SAS Institute Inc., Cary, NC, USA). Categorical variables are presented as frequencies and percentages and were compared using Pearson's chi-square test or Fisher's exact test when more than 20% of cells had an expected frequency below five. Continuous variables were assessed for normality using the Shapiro–Wilk test. Normally distributed variables are presented as mean ± standard deviation and compared using one-way analysis of variance (ANOVA) with Bonferroni correction for post-hoc comparisons. Non-normally distributed variables are presented as median (interquartile range, IQR) and compared using the Kruskal–Wallis test with Dunn's test for post-hoc analysis.

Univariate comparisons were first performed by injury severity group and by anatomical subsite of lower extremity injury. Descriptive statistics for injury distribution were subsequently presented for occupants with confirmed lower extremity injury at each subsite. Multivariable logistic regression models were constructed for each anatomical subsite, incorporating variables with p<0.10 in univariate analysis and those deemed clinically relevant. Where sparse data or insufficient reference group size resulted in estimation instability, Firth's penalized maximum likelihood estimation was applied [17]. Final models were derived using backward elimination. Results are reported as odds ratios (ORs) with 95% confidence intervals (CIs). Statistical significance was set at p<0.05. Missing data were handled by listwise deletion after confirming the proportion of missing values for each variable.

III. RESULTS

A total of 462 COE light truck occupants were included in the analysis. Lower extremity injuries were identified in 149 occupants (32.3%), whilst 313 occupants (67.7%) sustained no lower extremity injury.

Compared with occupants without lower extremity injuries, occupants with lower extremity injuries were more frequently male (90.6% vs. 81.8%, p=0.014) and more often had frontal airbag deployment (14.8% vs. 6.4%, p=0.004). Frontal collisions were more prevalent in the injured group (85.6% vs. 63.9%, p<0.001), and vehicle deformation was more severe, with a CDC extent ≥6 observed in 87.3% vs. 47.0% of cases (p<0.001). Mean delta-V was also significantly higher in the injured group (37.2 vs. 21.9 km/h, p<0.001). Occupants with lower extremity injuries had lower initial Glasgow Coma Scale scores and systolic blood pressure, and higher rates of hypotension, severe injury, hospitalization, and death (all p<0.01). Age, height, weight, body mass index, seatbelt use, vehicle age, and seating position did not differ significantly between groups. Among the 462 COE light truck occupants, 363 were drivers, 89 were front passengers, and 10 were second-row passengers (Table 1).

TABLE I
General characteristics of cab-over-engine light truck occupants by lower extremity injury status

Variables		Non-Lower Extremity Injury (N=313) N	%	Lower Extremity Injury (N=149) N	%	p-value
Sex	Male	256	81.79	135	90.6	0.0141
	Female	57	18.21	14	9.4	
Age	Median [IQR*]	56	[47-63]	54	[43-62]	0.1964
Age Group	15-39	51	16.29	32	21.48	0.3793
	40-64	193	61.66	88	59.06	
	65+	69	22.04	29	19.49	
Height	Median [IQR]	168	[163-174]	169	[163-174]	0.4551
Weight	Median [IQR]	68	[60-74]	68	[63-76]	0.2806
BMI**	Median [IQR]	23.88	[21.9-26.1]	24.15	[22.49-26.26]	0.2916
BMI Group	Underweight	4	1.83	0	0	0.3966
	Normal weight	79	36.07	34	31.48	
	Overweight	58	26.48	30	27.78	
	Obese	78	35.62	44	40.74	
Seatbelt	Unfastening	98	32.03	52	35.86	0.4193
	Fastening	208	67.97	93	64.14	
Frontal Airbag	Undeployment	291	93.57	127	85.23	0.0037
	Deployment	20	6.43	22	14.77	

	Median [IQR]	2012	[2007-2015]	2013	[2010-2016]	0.2812
Product Year	<2012	93	43.26	32	32.32	0.0659
	≥2012	122	56.74	67	67.68	
Seating Position	Driver	241	77	122	81.88	0.2290
	Frontal Passenger	63	20.13	26	17.45	
	Second row Passenger	9	2.88	1	0.67	
Collision type	Frontal	200	63.9	129	85.58	<.0001
	Left	30	9.58	5	3.36	
	Right	21	6.71	1	0.67	
	Rear-end	31	9.9	1	0.67	
	Rollover	80	9.9	22	8.72	
Extent	Median [IQR]	5	[3-6]	7	[6-7]	<.0001
CDC*** Extent	1-3	91	29.07	6	4.03	<.0001
	4-5	75	23.96	13	8.75	
	6+	147	46.96	130	87.25	
Delta V	Mean [Std]	21.85	[18.08]	37.2	[24.21]	<.0001
GCS	Median [IQR]	15	[15-15]	15	[15-15]	0.0074
GCS**** Group	13-15	278	96.86	123	88.49	0.0080
	9-12	3	1.05	4	2.88	
	3-8	6	2.09	12	8.63	
SBP*****	Median [IQR]	145	[129-162]	130	[110-150]	<.0001
SBP Group	<90	12	4.2	19	13.38	0.0006
	90+	274	95.8	123	86.62	
Emergency Room Result	Discharge	99	33.22	8	5.56	<.0001
	Transfer	28	9.4	21	14.58	
	Admission	161	54.03	103	71.53	
	Death	10	3.36	12	8.33	
ISS	<16	263	87.96	88	59.46	<.0001
	≥16	36	12.04	60	40.54	

*IQR: Interquartile Range

**BMI: Body Mass Index

***CDC: Collision Deformation Classification

****GCS: Glasgow Coma Scale

*****SBP: Systolic Blood Pressure

Injury patterns by anatomical subsite are presented in Table 2. The pelvic injury group (n=58) had relatively higher rates of non-seatbelt use, frontal airbag deployment, and an Injury Severity Score (ISS) ≥16. The femur injury group (n=35) similarly showed higher rates of airbag deployment and severe injury. No distinct univariate pattern was observed in the knee/patella injury group (n=27). Lower leg injuries (n=89) and foot/ankle injuries (n=47) occurred predominantly in frontal collisions with severe vehicle deformation; CDC extent ≥6 was observed in 95.5% and 93.2% of cases, respectively. Lower leg injuries were also associated with a delta-V ≥20 km/h, whilst foot/ankle injuries were most common in occupants aged 40–64 years (52.3%). Overall, distal lower extremity injuries, particularly lower leg and foot/ankle injuries, were predominantly observed in high-energy frontal collisions with severe vehicle deformation. In contrast, pelvic injuries were more frequent among occupants with non-seatbelt use, frontal airbag deployment, and ISS ≥16, whereas femur/thigh injuries were more frequent among occupants with frontal airbag deployment and ISS ≥16 (Table 2).

TABLE II

Distribution of lower extremity injuries by anatomical subsite and crash characteristics

Variables		Pelvis (N=58)		Femur/Thigh (N=35)		Knee/Patella (N=27)		Lower Leg (Tibia & Fibula) (N=89)		Foot/Ankle (N=47)	
		N	%	N	%	N	%	N	%	N	%
Sex	Male	54	93.1	32	91.43	26	96.3	80	89.89	41	93.18
	Female	4	6.9	3	8.57	1	3.7	9	10.11	3	6.62
Age Group	15~39	14	24.14	8	22.86	6	22.22	13	14.61	13	29.55
	40~65	29	50	19	54.29	15	55.56	58	65.17	23	52.27
	65+	15	25.86	8	22.86	6	22.22	18	20.22	8	18.18
Seatbelt	Unfastening	27	46.55*	10	30.3	7	29.17	27	31.4	17	39.53
	Fastening	31	53.45*	23	69.7	17	70.83	59	68.6	26	60.47
Frontal Airbag	Undeployment	45	77.59*	26	74.29*	23	85.19	73	82.02*	34	72.34*
	Deployment	13	22.41*	9	25.71*	4	14.81	16	17.98*	13	27.66*
Collision type	Frontal	47	81.03	31	88.57	21	77.78	81	91.01*	40	90.91*
	Left	4	6.9	0	0	1	3.7	0	0*	0	0*
	Right	0	0	0	0	1	3.7	0	0*	0	0*
	Rear-end	0	0	0	0	1	3.7	0	0*	0	0*
	Rollover	7	12.07	4	11.43	3	11.11	8	8.99*	4	9.09*
CDC Extent	1-3	2	3.45*	0	0*	3	11.11*	1	1.12*	0	0*
	4-5	6	10.34*	2	5.71*	1	3.7*	3	3.37*	3	6.82*
	6+	50	86.21*	33	94.29*	23	85.19*	85	95.51*	41	93.18*
Delta-V	<20 km/h	3	15.79*	4	30.77	4	40	11	23.4*	6	28.57
	20 km/h +	16	84.21*	9	69.23	6	60	36	76.6*	`15	71.43
ISS	<16	26	44.83*	16	45.71*	18	66.67	54	61.36*	31	65.96*
	≥16	32	55.17*	19	54.29*	9	33.33	34	38.64*	16	34.04*

* Statistically significant (p<0.05)

In multivariable analysis, CDC extent ≥6 showed the strongest association with overall lower extremity injury (OR 48.85, 95% CI 5.76–414.67). CDC extent 4–5 was also significantly associated with overall lower extremity injury (OR 12.48, 95% CI 1.77–88.25). With respect to anatomical subsites, frontal airbag deployment was independently associated with overall lower extremity injury (OR 3.41, 95% CI 1.56–7.45), pelvic injury (OR 3.18, 95% CI 1.36–7.41), and foot/ankle injury (OR 4.48, 95% CI 2.05–9.79). Seatbelt use was protective against overall lower extremity injury (OR 0.39, 95% CI 0.22–0.72). Left lateral collision was independently associated with overall lower extremity injury (OR 28.82, 95% CI 4.22–196.65). The age group 40–64 years showed a protective effect against foot/ankle injury (OR 0.47, 95% CI 0.22–0.99). Overall, vehicle deformation severity was the most consistent factor associated with lower extremity injury, whereas frontal airbag deployment, seatbelt use, age group, and collision direction showed selected subsite-specific associations (Table 3).

Because frontal impacts accounted for the majority of crashes, an additional sensitivity analysis restricted to frontal impacts was performed. This analysis included 320 occupants, comprising 194 occupants without lower extremity injury and 126 occupants with lower extremity injury. In the frontal-impact-only analysis, occupants with lower extremity injuries had more severe vehicle deformation than those without lower extremity injuries; CDC extent ≥6 was observed in 93.7% of occupants with lower extremity injury and 65.5% of occupants without lower extremity injury. Mean delta-V was also higher in the lower extremity injury group.

In multivariable analysis restricted to frontal impacts, CDC extent ≥6 remained independently associated with overall lower extremity injury. Frontal airbag deployment was independently associated with pelvic injury and foot/ankle injury. These findings were broadly consistent with the primary all-direction analysis, supporting the association between severe vehicle deformation and lower extremity injury occurrence in COE light truck occupants. The detailed results of the frontal-impact-only sensitivity analysis are presented in Appendix Table A.

TABLE III
Logistic regression analysis for risk factors associated with lower extremity injury by anatomical subsite

Predictor	Category	Any lower-extremity injury	Pelvis	Femur/Thigh	Knee/Patella	Lower leg (Tibia & Fibula)	Foot/Ankle
Sex	ref: Male						
	Female	0.51 (0.18–1.40)	0.87 (0.29–2.63)	0.42 (0.09–1.95)	0.43 (0.10–1.94)	0.85 (0.39–1.84)	0.63 (0.21–1.94)
Age group	ref: 15–39						
	40–64	0.55 (0.26–1.14)	0.63 (0.26–1.48)	0.84 (0.31–2.25)	2.26 (0.11–45.13)	1.49 (0.75–2.95)	0.47 (0.22–0.99)*
	≥65	1.10 (0.48–2.53)	1.02 (0.38–2.77)	1.22 (0.39–3.80)	2.12 (0.12–37.80)	1.50 (0.66–3.38)	0.59 (0.23–1.51)
Seatbelt	ref: Unfastening						
	Fastening	0.39 (0.22–0.72)*	1.03 (0.49–2.19)	1.09 (0.47–2.52)	1.10 (0.48–2.51)	1.05 (0.61–1.78)	0.64 (0.33–1.24)
Frontal airbag	ref: Undeployment						
	Deployment	3.41 (1.56–7.45)*	3.18 (1.36–7.41)*	1.54 (0.53–4.44)	1.50 (0.52–4.31)	1.93 (0.94–3.93)	4.48 (2.05–9.79)*
Collision type	ref: Frontal						
	Left	28.82 (4.22–196.65)*	1.59 (0.07–38.63)	0.72 (0.03–19.63)	0.63 (0.03–16.01)	0.18 (0.01–4.07)	1.41 (0.06–34.23)
	Right	1.08 (0.04–26.26)	1.48 (0.07–33.51)	2.87 (0.26–32.14)	2.85 (0.26–31.71)	0.23 (0.01–5.00)	0.99 (0.05–20.99)
	Rear-end	1.54 (0.07–33.29)	1.45 (0.06–33.35)	2.21 (0.18–27.31)	2.19 (0.19–25.50)	0.17 (0.01–3.77)	1.09 (0.04–27.87)
	Rollover	1.55 (0.62–3.88)	1.39 (0.48–4.07)	1.70 (0.53–5.48)	1.50 (0.47–4.85)	0.99 (0.43–2.32)	0.96 (0.32–2.87)
Extent	ref: 1–3						
	4–5	12.48 (1.77–88.25)*	3.67 (0.25–54.19)	0.77 (0.07–8.22)	0.79 (0.08–8.20)	0.54 (0.08–3.67)	4.16 (0.28–61.42)
	≥6	48.85 (5.75–414.67)*	12.33 (0.84–180.67)	3.29 (0.38–28.80)	3.27 (0.39–27.69)	4.52 (0.86–23.78)	12.79 (0.88–187.08)

* Statistically significant ($p<0.05$)

IV. DISCUSSION

The most consistent factor associated with lower extremity injury in COE light truck occupants in this KIDAS-based study was severe vehicle deformation, as represented by CDC extent. In the overall analysis including all injury severities, both moderate and severe vehicle deformation were independently associated with overall lower extremity injury. Specifically, CDC extent 4–5 and CDC extent ≥6 were associated with increased odds of lower extremity injury, with the strongest association observed for CDC extent ≥6. These findings suggest a dose-related pattern in which greater vehicle deformation is associated with a higher likelihood of lower extremity injury. When the analysis was stratified by overall injury severity, CDC extent ≥6 remained associated with overall lower extremity injury in the non-severe injury group (ISS <16), showing an approximately five-fold increase in odds (OR 4.99, 95% CI 1.07–23.26). These findings are consistent with existing biomechanical literature demonstrating that greater structural deformation is associated with increased lower extremity injury risk [6,17]. Footwell and toe pan intrusion in frontal collisions are established mechanisms for lower leg and foot/ankle injuries, whilst instrument panel intrusion has been associated with knee–femur–hip injuries [7,18]. In the present study, foot/ankle injuries were predominantly observed in frontal collisions with severe vehicle deformation, which is biomechanically compatible with possible pedal-area or footwell intrusion mechanisms. However, direct measurements of pedal intrusion, footwell intrusion, or occupant compartment intrusion were not available in the present dataset. Therefore, the influence of pedal intrusion on foot/ankle injury outcomes could not be directly evaluated. CDC extent, as used in this study, should be interpreted as a surrogate measure of crash severity and vehicle deformation rather than direct evidence of pedal, footwell, or occupant compartment intrusion. In the severe injury group (ISS ≥16), the inability to derive estimates for CDC extent ≥6 in certain subsites reflects statistical instability arising from insufficient sample sizes in the reference group, and is itself suggestive of a pattern in which severe injuries occur predominantly under conditions of substantial structural deformation.

Because frontal impacts accounted for most cases, we performed an additional sensitivity analysis restricted to frontal impacts. The results were broadly consistent with the primary all-direction analysis: severe vehicle deformation remained associated with overall lower extremity injury, and frontal airbag deployment was associated with pelvic and foot/ankle injuries. However, because restricting the analysis to frontal impacts reduced the sample size and resulted in less stable subsite-specific estimates, the all-direction analysis was retained as the primary analysis

Frontal airbag deployment was independently associated with overall lower extremity injury, pelvic injury, and foot/ankle injury. These associations, however, are more appropriately interpreted as reflecting the conditions of high-severity frontal collisions that meet the airbag deployment threshold, rather than a direct injurious effect of the airbag itself [19]. In the non-severe injury group, associations between airbag deployment and both pelvic and foot/ankle injuries were more clearly observed, whereas in the severe injury group, a significant association was identified only for foot/ankle injury. This suggests that the pattern of restraint system effects may vary according to collision severity, and supports the need to evaluate restraint system design specifically for COE light trucks.

Seatbelt use demonstrated an independent protective association with overall lower extremity injury in the non-severe group (OR 0.36, 95% CI 0.16–0.84); however, a consistent protective effect was not observed across all anatomical subsites. In particular, a protective association with pelvic injury was identified in the non-severe group but was not significant in the severe group. These findings are consistent with prior studies suggesting that the protective effect of seatbelts against lower extremity injury may be less consistent than for other body regions [20]. However, this interpretation should be applied cautiously to lateral impacts, because seatbelt performance may differ according to occupant-specific near-side or far-side conditions. In exploratory near-side/far-side analyses, estimates were unstable with wide confidence intervals; therefore, no definitive conclusion can be drawn regarding seatbelt effectiveness in lateral collisions.

Left lateral collision was independently associated with overall lower extremity injury and with pelvic injury in the severe group. Although prior studies have reported higher rates of pelvic and femur injuries in lateral collisions [21], the number of lateral-impact cases in the present study was limited, resulting in wide confidence intervals. In the primary analysis, lateral impacts were classified according to the side of vehicle deformation recorded in the CDC data. Although an exploratory near-side/far-side analysis was additionally performed using seating position, the resulting estimates were unstable with wide confidence intervals because of the limited number of lateral-impact cases. Therefore, findings related to lateral impacts should be interpreted cautiously as exploratory associations, and no definitive conclusion can be drawn regarding laterality-specific injury mechanisms.

In the severe injury group (ISS ≥16), significant associations were identified for only a limited number of subsites, and statistical significance was not reached for most variables. This should not be interpreted as an absence of predictive factors, but rather as a consequence of limited sample size, low event counts, and the simultaneous contribution of multiple injury mechanisms in high-energy collisions, which preclude reliable estimation of the independent effect of individual variables.

Several limitations of this study warrant consideration. First, as a retrospective study using a single database, the influence of unmeasured confounders such as impact velocity cannot be excluded. Second, CDC extent was used as a surrogate measure in the absence of direct measurements of structural deformation such as footwell intrusion. Third, sparse data in some subgroup analyses may have resulted in model instability. Several odds ratios had wide or extremely wide confidence intervals, particularly in analyses stratified by injury severity and anatomical subsite. Although Firth's penalized maximum likelihood estimation was used to reduce small-sample bias when estimation instability occurred, the resulting estimates remain imprecise when event counts are low. Therefore, subgroup-specific findings should be interpreted cautiously as exploratory associations rather than definitive or precise effect estimates, and confirmation in larger datasets is warranted. Fourth, detailed restraint system specifications and occupant kinematic data were unavailable.

V. CONCLUSION

This study used the KIDAS database to analyse lower extremity injuries in cab-over-engine (COE) truck occupants by anatomical subsite and to evaluate differences in associated factors according to overall injury severity. Severe vehicle deformation, as represented by CDC extent ≥6, was the most consistent factor associated with overall lower extremity injury in the non-severe injury group. Frontal airbag deployment, seatbelt use, and collision direction showed varying associations according to injury severity and anatomical subsite. These findings indicate that lower extremity injury patterns among COE truck occupants differ by anatomical subsite and appear to be influenced by crash severity and restraint-related factors.

Because crash speed, impact energy, occupant compartment intrusion, and detailed restraint-system characteristics were not directly measured, these results should be interpreted as epidemiologic associations rather than direct evidence of specific injury mechanisms or protective effects. Future research using detailed crash reconstruction and vehicle intrusion data is needed to better understand the relationship between COE vehicle structure, restraint-system performance, and lower extremity injury occurrence.

VI. ACKNOWLEDGEMENTS

We would like to extend our gratitude to our supervisor and colleagues at Center for Automotive Medical Science for their valuable ideas and advice, and to the KIDAS data collection team for their dedicated efforts in compiling the database used in this study.

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VIII. APPENDIX

TABLE AI

Distribution of lower extremity injuries by anatomical subsite in non-severe injury group (ISS<16)

		Pelvis (N=26)		Femur/Thigh (N=16)		Knee/Patella (N=18)		Lower Leg (Tibia & Fibula) (N=54)		Foot/Ankle (N=28)	
Variables		N	%	N	%	N	%	N	%	N	%
Sex	Male	24	7.92	15	93.75	17	94.44	46	83.64	25	89.29
	Female	2	7.69	1	6.25	1	5.56	9	16.36	3	10.71
Age Group	15~39	6	23.08	2	12.5	3	16.37	7	12.73	9	32.14
	40~65	11	42.31	8	50	10	55.56	35	63.64	14	50
	65+	9	34.62	6	37.5	5	27.78	13	23.64	5	17.86
Seatbelt	Unfastening	13	50*	4	28.57	2	13.33	18	33.96	11	39.29
	Fastening	13	50*	10	71.43	13	86.67	35	66.04	17	60.71
Frontal Airbag	Undeployment	19	73.08*	13	81.25	16	88.89	46	83.64*	21	75*
	Deployment	7	26.92*	3	18.75	2	11.11	9	16.36*	7	25*
Collision type	Frontal	23	88.46	16	100	14	77.78	50	90.91*	27	87.1
	Left	0	0	0	0	1	5.56	0	0*		
	Right	0	0	0	0	1	5.56	0	0*	0	0
	Rear-end	0	0	0	0	1	5.56	0	0*	0	0
	Rollover	3	11.54	0	0	1	5.56	5	9.09*	3	9.68
CDC Extent	1-3	0	0*	0	0*	3	16.67	1	1.82*	0	0*
	4-5	3	11.54*	2	12.5*	1	5.56	2	3.64*	2	7.14*
	6+	23	88.46*	14	87.5*	14	77.78	52	94.55*	26	92.86*
Delta-V	<20 km/h	2	40	3	50	4	66.67	10	33.33*	5	33.33
	20 km/h +	3	60	3	50	2	33.33	20	66.67*	10	66.67

TABLE AII
Distribution of lower extremity injuries by anatomical subsite in severe injury group (ISS≥16)

Variables		Pelvis (N=32) N	Pelvis %	Femur/Thigh (N=19) N	Femur/Thigh %	Knee/Patella (N=9) N	Knee/Patella %	Lower Leg (Tibia & Fibula) (N=34) N	Lower Leg %	Foot/Ankle (N=16) N	Foot/Ankle %
Sex	Male	30	93.75	17	89.47	9	100	34	100*	16	100
	Female	2	6.25	2	10.53	0	0	0	0*	0	0
Age Group	15~39	8	25	6	31.58	3	3.33	6	17.65	4	25
	40~64	18	56.25	11	57.89	5	55.55	23	67.65	9	56.25
	65+	6	18.75	2	10.53	1	11.11	5	14.71	3	18.75
Seatbelt	Unfastening	14	43.75	6	31.58	5	55.56	9	27.27*	6	40
	Fastening	18	56.25	13	68.42	4	44.44	24	72.73*	9	60
Frontal Airbag	Undeployment	26	81.25	13	68.42*	7	77.78	30	81.08	10	62.5*
	Deployment	6	18.75	6	31.58*	2	22.22	7	18.92	6	37.5*
Collision type	Frontal	24	75*	15	78.95	7	77.78	31	91.18	13	81.25
	Left	4	12.5*	0	0	0	0	0	0	0	0
	Right	0	0*	0	0	0	0	0	0	0	0
	Rear-end	0	0*	0	0	0	0	0	0	0	0
	Rollover	4	12.5*	4	21.05	2	22.22	3	8.82	3	18.75
CDC Extent	1-3	2	6.25	0	0	0	0	0	0*	0	0
	4-5	3	9.38	0	0	0	0	1	2.94*	1	6.25
	6+	27	84.38	19	100	9	100	33	97.06*	15	93.75
Delta-V	<20 km/h	1	7.14	1	14.29	0	0	1	5.88	1	16.67
	20 km/h +	13	92.86	6	85.71	4	100	16	94.12	5	83.33

TABLE AIII

Logistic regression analysis for risk factors associated with lower extremity injury by anatomical subsite in non-severe injury group (ISS<16)

Predictor	Category	Any lower-extremity injury	Pelvis	Femur/Thigh	Knee/Patella	Lower leg (Tibia & Fibula)	Foot/Ankle
Sex	ref: Male						
	Female	1.00 (0.47–2.15)	0.62 (0.17–2.27)	0.75 (0.16–3.43)	0.62 (0.13–2.88)	1.61 (0.69–3.75)	1.08 (0.34–3.38)
Age group	ref: 15–39						
	40–64	0.80 (0.41–1.59)	0.64 (0.23–1.79)	0.87 (0.22–3.46)	1.08 (0.28–4.17)	1.61 (0.66–3.89)	0.47 (0.19–1.16)
	≥65	1.16 (0.51–2.59)	1.92 (0.64–5.82)	2.76 (0.68–11.31)	2.18 (0.52–9.24)	2.07 (0.75–5.71)	0.55 (0.18–1.69)
Seatbelt	ref: Unfastening						
	Fastening	0.79 (0.45–1.38)	0.36 (0.16–0.84)*	1.03 (0.36–2.99)	2.49 (0.72–8.61)	0.77 (0.40–1.50)	0.67 (0.30–1.50)
Frontal airbag	ref: Undeployment						
	Deployment	2.36 (1.01–5.50)*	4.82 (1.67–13.90)*	2.47 (0.68–8.92)	1.21 (0.29–4.96)	1.99 (0.81–4.93)	3.31 (1.23–8.95)*
Collision type	ref: Frontal						
	Left	0.16 (0.01–3.33)	2.30 (0.07–76.14)	1.31 (0.04–40.18)	0.58 (0.02–20.42)	0.19 (0.01–4.89)	2.03 (0.07–61.39)
	Right	0.65 (0.08–5.50)	1.58 (0.06–45.31)	1.86 (0.06–58.71)	3.88 (0.21–71.44)	0.28 (0.01–7.35)	2.03 (0.07–57.11)
	Rear-end	0.49 (0.06–4.15)	2.07 (0.08–55.65)	1.18 (0.05–29.96)	2.06 (0.13–32.72)	0.22 (0.01–5.53)	2.01 (0.06–70.13)
	Rollover	0.93 (0.37–2.34)	1.75 (0.48–6.34)	0.33 (0.02–4.58)	1.25 (0.23–6.65)	1.28 (0.44–3.68)	0.56 (0.10–3.01)
Extent	ref: 1–3						
	4–5	1.39 (0.28–6.76)	4.99 (0.32–78.01)	4.62 (0.29–73.10)	1.01 (0.08–12.89)	0.40 (0.05–3.19)	4.63 (0.26–81.44)
	6+	4.99 (1.07–23.26)*	12.76 (0.72–225.33)	6.06 (0.33–110.14)	2.75 (0.21–36.39)	3.76 (0.64–22.06)	15.60 (0.76–318.84)

* Statistically significant ($p<0.05$)

TABLE AIV

Logistic regression analysis for risk factors associated with lower extremity injury by anatomical subsite in severe injury group (ISS≥16)

Predictor	Category	Any lower-extremity injury	Pelvis	Femur/Thigh	Knee/Patella	Lower leg (Tibia & Fibula)	Foot/Ankle
Sex	ref: Male						
	Female	0.19 (0.04–0.96)*	0.62 (0.11–3.46)	1.23 (0.21–7.10)	0.33 (0.02–7.19)	0.06 (0.00–1.20)	0.14 (0.01–4.41)
Age group	ref: 15–39						
	40–64	0.39 (0.08–1.88)	0.37 (0.11–1.24)	0.47 (0.13–1.70)	0.36 (0.08–1.73)	1.27 (0.36–4.50)	0.35 (0.08–1.51)
	≥65	0.14 (0.02–0.79)*	0.37 (0.09–1.60)	0.27 (0.05–1.52)	0.30 (0.04–2.24)	0.62 (0.14–2.78)	0.44 (0.08–2.49)
Seatbelt	ref: Unfastening						
	Fastening	1.54 (0.56–4.22)	0.67 (0.25–1.77)	1.16 (0.38–3.55)	0.38 (0.10–1.46)	2.49 (0.91–6.80)	0.76 (0.23–2.56)
Frontal airbag	ref: Undeployment						
	Deployment	0.68 (0.18–2.56)	2.05 (0.59–7.15)	3.15 (0.83–12.00)	1.89 (0.35–10.18)	1.92 (0.51–7.29)	6.09 (1.56–23.80)*
Collision type	ref: Frontal						
	Left	14.84 (0.35–625.64)	52.61 (1.23–>999.99)*	2.10 (0.03–143.24)	2.89 (0.04–186.52)	0.24 (0.01–11.47)	0.98 (0.02–42.98)
	Right	0.04 (<0.001–1.98)	0.33 (0.01–12.31)	0.71 (0.02–31.76)	1.56 (0.04–65.06)	0.20 (0.01–6.40)	0.71 (0.02–23.60)
	Rear-end	–	1.41 (0.01–424.67)	9.60 (0.05–>999.99)	–	0.23 (<0.001–556.96)	3.72 (0.03–451.05)
	Rollover	0.66 (0.16–2.67)	1.07 (0.27–4.33)	2.38 (0.52–10.93)	1.97 (0.36–10.69)	0.51 (0.12–2.27)	1.23 (0.26–5.90)
Extent	ref: 1–5						
	6+	3.04 (0.55–16.97)	2.58 (0.37–17.89)	3.61 (0.23–57.06)	3.09 (0.20–47.67)	1.96 (0.28–13.56)	1.27 (0.15–10.62)

* Statistically significant ($p<0.05$)

TABLE AV

Logistic regression analysis for risk factors associated with lower extremity injury by anatomical subsite — Frontal collision cases only

Predictor	Category	Any lower-extremity injury	Pelvis	Femur/Thigh	Knee/Patella	Lower leg (Tibia & Fibula)	Foot/Ankle
Sex	ref: Male						
	Female	0.74 (0.26–2.12)	0.62 (0.11–3.46)	0.98 (0.31–3.09)	0.45 (0.10–2.06)	0.84 (0.36–1.95)	0.68 (0.21–2.16)
Age group	ref: 15–39						
	40–64	0.45 (0.21–0.98)*	0.37 (0.11–1.24)	0.73 (0.28–1.91)	2.64 (0.13–52.83)	1.61 (0.77–3.38)	0.44 (0.20–0.98)*
	≥65	1.04 (0.43–2.51)	0.37 (0.09–1.60)	1.33 (0.45–3.92)	2.38 (0.13–42.08)	1.72 (0.72–4.14)	0.63 (0.24–1.66)
Seatbelt	ref: Unfastening						
	Fastening	0.58 (0.30–1.11)	0.67 (0.25–1.77)	1.05 (0.47–2.34)	1.05 (0.48–2.32)	1.12 (0.63–1.98)	0.62 (0.31–1.26)
Frontal airbag	ref: Undeployment						
	Deployment	2.74 (1.17–6.42)*	2.05 (0.59–7.15)	2.15 (0.81–5.66)	1.91 (0.72–5.09)	1.33 (0.61–2.90)	3.57 (1.51–8.43)*
Extent	ref: 1–3						
	4–5	1.20 (0.05–28.00)	0.67 (0.25–1.77)	1.21 (0.06–26.86)	13.27 (0.74–239.63)	1.11 (0.05–25.79)	1.49 (0.07–31.65)
	6+	6.16 (0.34–113.15)	2.58 (0.37–17.89)	3.28 (0.18–57.42)	46.99 (2.18–>999.99)	11.49 (0.63–208.37)	3.85 (0.21–69.17)

* Statistically significant ($p<0.05$)