INJURY BIOMECHANICS RESEARCH

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Comparative Analysis of Male and Female Thoracic Injury and Causation Trends in Frontal Motor Vehicle Collisions

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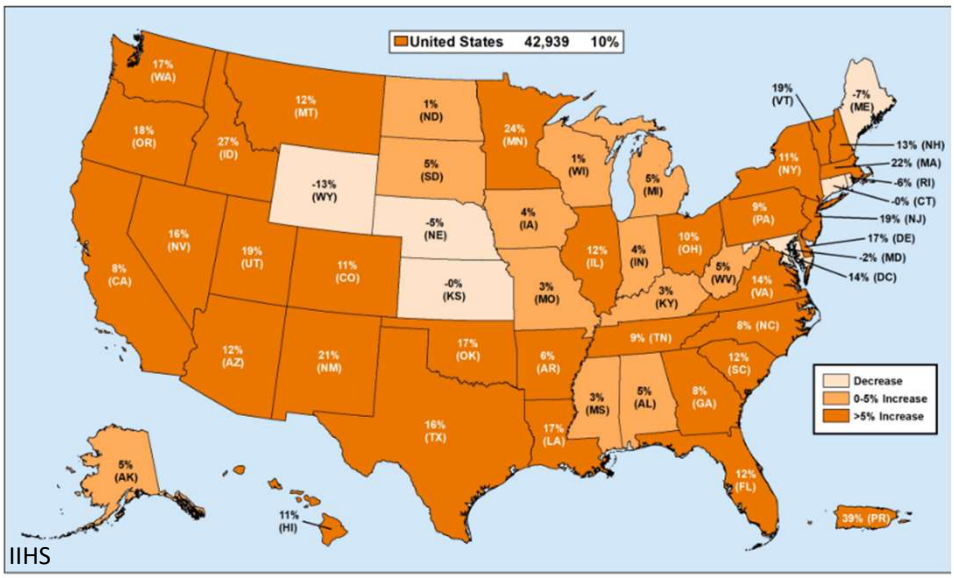
This study investigates the impact of sex on the prevalence and causation of thoracic injuries in frontal motor vehicle collisions (MVCs), using data from the Crash Injury Research and Engineering Network (CIREN). The research focuses on 460 front seat occupants (204 males, 256 females) involved in MVCs between 2005 and 2015, all sustaining thoracic injuries of AIS severity 2 or higher. It analyzes injury types (rib and sternum fractures, lung, heart, diaphragm, and vessel injuries) and the involved physical components (IPCs) causing these injuries, such as steering wheel, seatbelt, and airbag.

Results reveal females are more frequently belted and likely to be passengers. Although males sustain more lung injuries, the occurrence of other injury types shows no significant sex differences. Notably, females experience more right-sided rib fractures as belted drivers, while males have more left-sided fractures as belted passengers. Unbelted occupants display similar fracture patterns regardless of sex. Injury causation differed by sex as well, with males being significantly more often injured by the steering wheel, whereas females are more likely to be harmed by seatbelts.

The findings suggest that anatomical, physiological, and biomechanical differences between sexes influence the susceptibility and response to thoracic injuries in MVCs. This highlights the necessity of considering sex-specific differences in vehicle safety system design and occupant protection. The study advocates for detailed data collection on injury causation and mechanisms in MVCs to develop effective prevention and treatment strategies.

Introduction



IIHS

NHTSA

Vehicle Safety Continues to Improve

- Technological advancements
  - AEB, blind spot detection, etc.
- Material and/or design changes

MVC Fatalities Hit a 16-Year Peak

- **~43,000 fatalities; 2.5 million** injuries in 2021 alone
- **10% increase** nationally in motor vehicle collision (MVC) fatalities from 2020 to 2021

Are current vehicle and safety technologies effectively protecting all passengers?

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I'll start by highlighting a critical paradox in the realm of vehicle safety. Despite significant advancements in safety technologies, we are witnessing a troubling trend in motor vehicle collision (MVC) fatalities. As illustrated by the map on the left, each state is color-coded to represent the change in MVC fatalities from the previous year. The alarming fact is that the United States has experienced a 10% national increase in fatalities, with about 43,000 lives lost and 2.5 million injuries in 2021 — a 16-year high.

Now, reflecting on the advancements touted to improve vehicle safety. We've seen, for example, the integration of Automatic Emergency Braking (AEB), the introduction of sophisticated blind spot detection systems, alongside improvements in materials and engineering designs. These innovations have been engineered to protect passengers, to make vehicles safer, and to reduce the likelihood of fatal collisions. However, the data on this slide prompts a critical evaluation of these technologies. The increase in MVC fatalities raises an essential question about the real-world efficacy of our current vehicle safety systems. Are these technologies performing as intended? Are they accessible and effective across all vehicle models and demographics? And crucially, are they protecting all passengers equally? This is not just a question of technological capability but also of implementation, education, and policy.

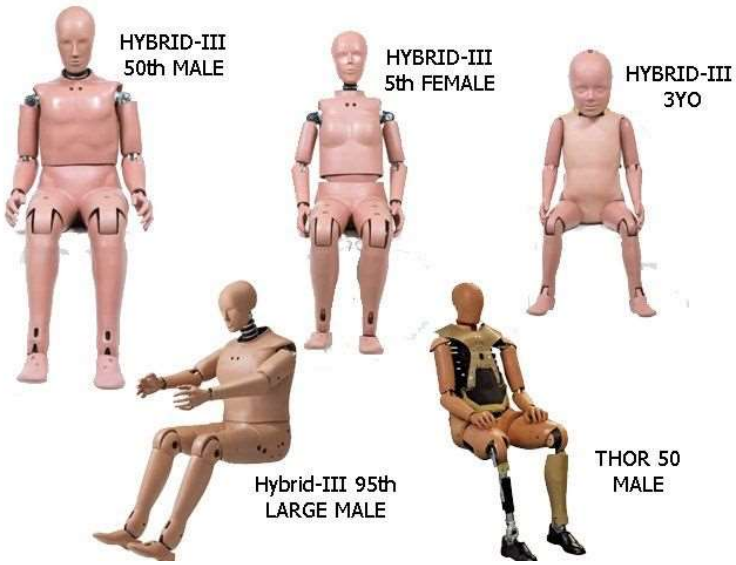
As researchers and professionals in the field of biomedical engineering, our goal is to understand the 'why' behind this data. The research so far has looked into many potential factors, but the question remains — with all these safety features, why are

MVC fatalities still on the rise?

The map here is more than a visual aid; it's a call to action. It challenges us to dig deeper, to look beyond the numbers and question the status quo of vehicle safety. The stark increase in fatalities across the nation, highlighted in darker shades, stands as a testament to the urgent need for a reassessment of our approach to vehicle safety.

In conclusion, this slide does not merely present data; it calls into question our confidence in current vehicle safety technologies and their role in protecting lives. It serves as a stark reminder that innovation must go hand-in-hand with effectiveness and that as we move forward, our strategies must be comprehensive, inclusive, and above all, effective in safeguarding every passenger on the road.

Introduction



Importance of Crash Test Dummies
- Realistic Impact Assessment
- Safety Feature Evaluation
- Injury Risk Identification
- Regulatory Compliance

Variety of Human Crash Test Dummies
- 50th and 95th percentile male
- 5th percentile female
- 3-year-old

Limited crash test dummies available for the average female

Problem: Average male crash test dummies used to represent average females

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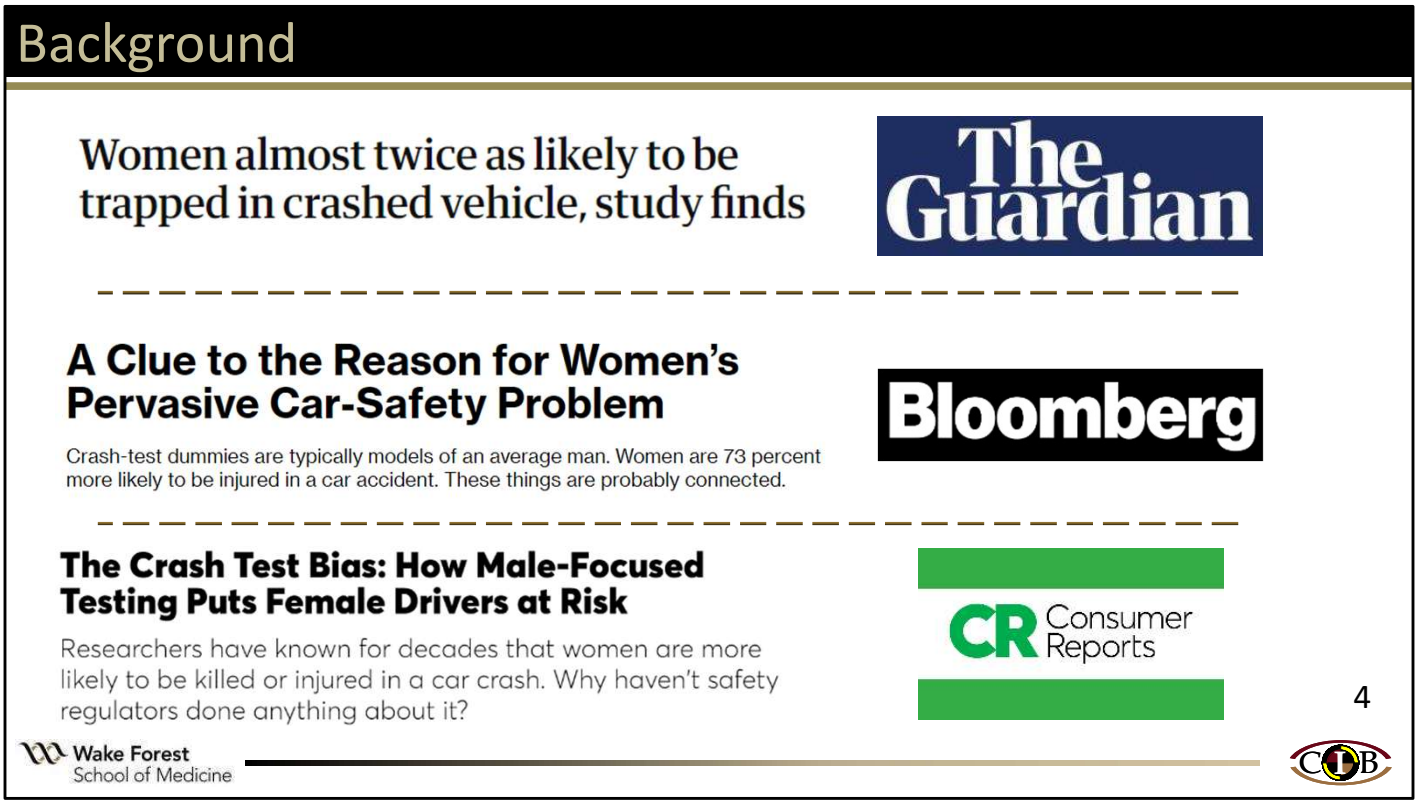
Now we'll shift our focus to a crucial but often overlooked aspect of vehicle safety testing – the representation of Anthropomorphic Test Devices, or ATDs, more commonly known as crash test dummies. On the left, we see a lineup of ATDs that are designed to represent a spectrum of human sizes and shapes. These range from the 50th percentile male, considered the average male, to the 5th percentile female, representing a smaller female, and even a 3-year-old child.

The use of these dummies is fundamental in realistic impact assessment, evaluation of safety features, identification of injury risks, and ensuring regulatory compliance. They are the tools that provide us with critical data on how a human body might respond in a vehicular collision. We have different dummies to reflect the variety in human physiques, the variety of which is essential to address the diversity of potential vehicle occupants.

However, the primary concern to emphasize is the limited availability of crash test dummies that accurately represent the average female — the 50th percentile female. This gap is not just a matter of missing metrics; it has profound implications for the safety of female vehicle occupants. The average female has different anatomical and physiological characteristics compared to the average male, which can affect injury patterns and outcomes.

It's a troubling reality that, in the design and testing of vehicle safety, it is somewhat common practice for manufacturers to use the 50th percentile male models as stand-ins for the average female. This practice does not account for the crucial differences in body structure and composition between sexes, leading to a potential oversight in

safety design and protection for female occupants.



As we delve further into the discussion of sex-differences in vehicle safety, it's essential to recognize the broader social impact this issue has garnered. Headlines from leading news outlets have started to cast a light on a problem that extends beyond engineering and regulatory communities, into the public arena.

Let us consider the weight of these statements. "Women almost twice as likely to be trapped in crashed vehicle, study finds," reports The Guardian, a stark statistic that is as alarming as it is revealing. Bloomberg presents a telling connection with "A Clue to the Reason for Women's Pervasive Car-Safety Problem," suggesting that the pervasive use of male models in safety testing is likely a contributing factor to the higher injury rates for women.

And perhaps most indicting is the headline from Consumer Reports: "The Crash Test Bias: How Male-Focused Testing Puts Female Drivers at Risk." It points out a known issue that has persisted for decades: women are more likely to be killed or injured in a car crash, and questions why safety regulators have not addressed this sex-specific bias.

These headlines are not mere news items; they are a public outcry, a demand for change in an industry that has long been predicated on a one-size-fits-all approach to safety; they underscore the critical need for inclusive testing that considers both the anatomical and physiological differences between sexes.

The media's vocalization of this issue is significant as it brings to light the broader implications of the biases in crash test methodologies and amplifies the urgency for reform. It is a call to action for manufacturers, safety regulators, and the biomedical

engineering community to acknowledge the problem and work towards solutions that ensure safety measures are comprehensive and protective of all vehicle occupants.

Background

Automobile injury trends in the contemporary fleet: Belted occupants in frontal collisions
Forman, J., Poplin, G., Shaw, G., McMurry, T., Schmidt, K., Ash, J., Sunnevang, C.

Females at a greater risk for AIS 2+ and 3+ injuries

Sex-Based Differences in Odds of Motor Vehicle Injury Outcomes
Craig, M. J., Liu, C., Zhang, F., Enriques, J.

Females had:
- Higher odds of AIS 2+ injury
- Higher odds of upper and lower extremity injury
- Lower odds of thorax/neck injury

Vulnerability of Female Drivers Involved in Motor Vehicle Crashes: An Analysis of US Population at Risk
Bose, D., Gomez, M., Crandall, J.

Females have 50% or higher odds of sustaining serious injury than males in comparable MVCs.

The discussion on sex-based disparities in vehicle safety is further reinforced by a growing body of research. We now turn our attention to three pivotal studies that shine a light on the significant differences in injury outcomes between males and females in motor vehicle crashes (MVCs).

The first study by Forman et Al., titled "Automobile injury trends in the contemporary fleet: Belted occupants in frontal collisions," provides a rigorous analysis of injury trends and reveals that females are at a heightened risk for AIS 2+ and 3+ injuries. This finding is particularly compelling, as it underscores the fact that even when safety measures are utilized, such as seat belts, discrepancies in injury severity persist.

The second paper, "Sex-Based Differences in Odds of Motor Vehicle Injury Outcomes,“, by Craig et Al., presents a detailed examination of the odds of injury. It emerges from this research that females have higher odds of sustaining AIS 2+ injuries and are more susceptible to lower extremity injuries. Conversely, they have lower odds of thorax and neck injuries. These distinctions are crucial, as they direct us to consider how safety designs may be tailored or modified to address specific vulnerabilities.

The third study we reference, by Bose et Al., is "Vulnerability of Female Drivers Involved in Motor Vehicle Crashes: An Analysis of US Population at Risk." It is a sobering revelation from this work that females have 50% or higher odds of sustaining serious injuries than males in comparable MVCs. Such a statistic is a stark reminder of the work that remains to be done in ensuring safety measures are

equitable and effective.

These research initiatives are instrumental in highlighting that while strides have been made to enhance vehicle safety for both males and females, there is a pressing need to continue this development. They serve as a clarion call to the automotive industry, safety regulators, and the biomedical engineering community to not only recognize but also actively address the disparities that exist in vehicle safety.

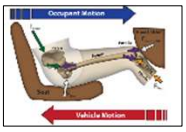
Methods: Data Source

Crash Injury Research and Engineering Network

CIREN The Nation's Largest Learning Laboratory

Investigates occupant kinematics, injuries, and ultimately determines the **causation of injuries** in severe motor vehicle collisions.





Inclusion Criteria

- CIREN Dataset (2005-2015)
- Newer vehicles (≤ 7 years old)
- First Row Occupants, 16+ years old
- Thoracic injuries w/ AIS 2+

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The approach to understanding vehicle collision outcomes and occupant safety has been significantly advanced by the Crash Injury Research and Engineering Network, known as CIREN. This organization plays a pivotal role in investigating the kinematics of occupants, the injuries sustained, and the causation of injuries in severe motor vehicle collisions. By dissecting the intricate details of crash events, CIREN aims to peel back the layers of immediate visual damage to reveal the undercurrents of injury mechanics.

CIREN's process begins with meticulous case admission protocols, where eligibility is screened, and consent for enrollment is obtained. This is followed by an exhaustive collection of medical record data, which includes detailed injury descriptions, radiology, and the course of hospital treatment. The next phase encompasses on-site crash investigation, involving the gathering of photographs, evidence, and precise measurements from the crash scene. This comprehensive approach allows for a multi-faceted examination of each incident.

The data and insights flow into the final phase, where engineering experts and clinicians come together to analyze and reach a consensus on injury causation and mechanisms. This collaborative effort culminates in a rich dataset that provides a fertile ground for research and innovation in vehicle safety.

For the study in question, the inclusion criteria are meticulously defined to ensure the relevance and quality of the data. The dataset spans a decade, from 2005 to 2015, and focuses on newer vehicles that are seven years old or newer. The population of interest includes first-row occupants who are 16 years or older, with a specific

emphasis on those who have sustained thoracic injuries rated at AIS 2+.

Methods: AIS Code Grouping

Abbreviated Injury Scale (AIS) Codes

Seven-digit code based on its anatomical location and its severity

450210.2
Multiple rib fractures

Severity

450299.1	**Rib Cage** NFS
450289.1	contusion
450210.2	multiple rib fractures NFS
450200.1	fracture(s) without flail, any location unilateral or bilateral NFS
450201.1	one rib [*OIS I*]
450202.2	two ribs [*OIS I*]
450203.3	≥3 ribs [*OIS II*]
450209.3	fractures with flail NFS
450211.3	unilateral flail chest NFS [*OIS IV*]
450212.3	3-5 flail ribs [*OIS IV*]
450213.4	>5 flail ribs [*OIS IV*]
450214.5	bilateral flail chest [*OIS V*]

Rib Fracture	Sternum Fracture	Hemo/ Pneumothorax	Lung Injury	Heart Injury	Diaphragm Injury	Vessel Injury

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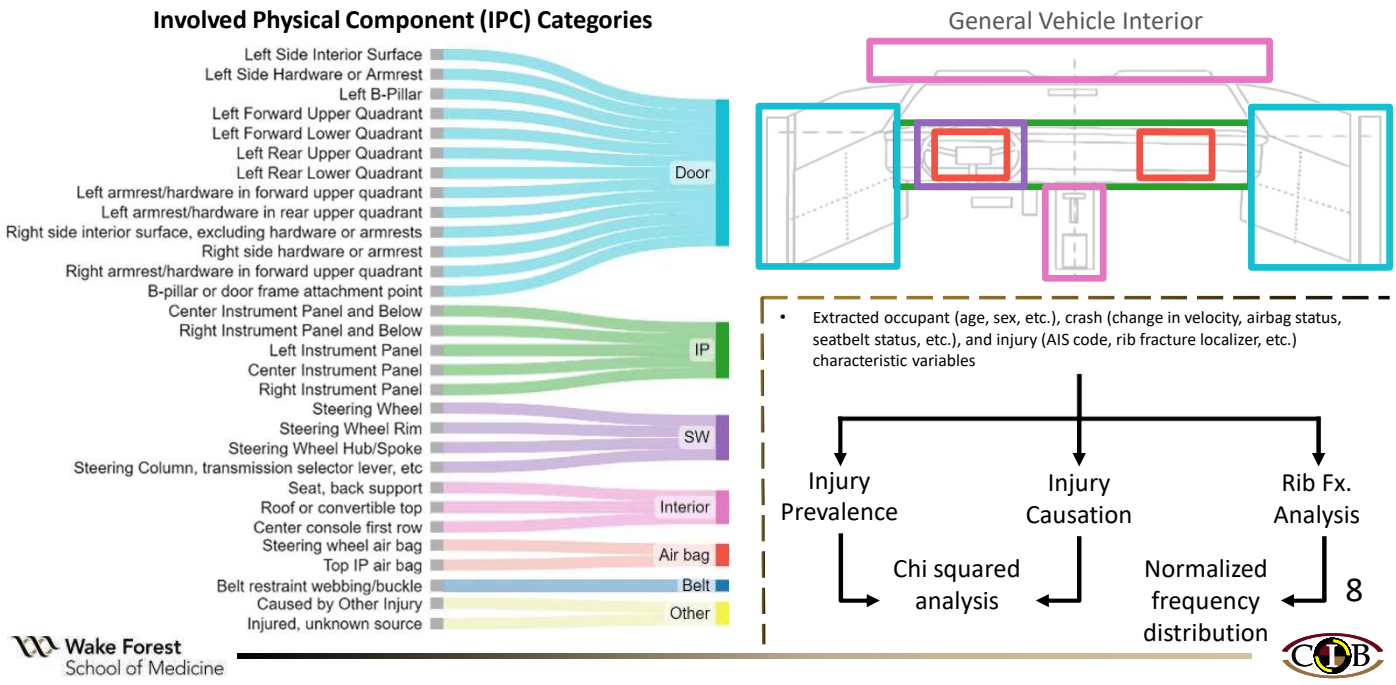
Injury assessment in motor vehicle collisions is standardized through the Abbreviated Injury Scale (AIS), which employs a seven-digit code to provide precise and consistent data regarding the anatomical location and severity of injuries. The AIS codes form a foundational element in the classification of injuries, enabling researchers and clinicians to quantify and categorize the impacts of a collision on the human body.
In the bottom left, you can see an example of how the AIS code operates with the code for multiple rib fractures, 450210.2. Here, the first six digits detail the specific injury, with the final digit, in this case, a '2', indicating the severity level on a scale that ranges from 1, denoting minor, to 6, which signifies maximal severity.
Given the variety of AIS codes that can describe similar or related injuries, a methodological consolidation is essential. This approach simplifies data analysis by amalgamating all codes pertaining to rib fractures into a single binary variable which then indicates whether an occupant experienced a rib fracture. The same consolidation process applies to other thoracic injury regions and categories, streamlining the vast array of possible injury codes into more manageable groupings. This method allows for a more straightforward and impactful analysis, ensuring that the data reflects a clear and accurate picture of injury occurrences and their severities.

Methods: IPC Categorization



Like AIS codes, due to the multitude of individual interior components, also known as Involved Physical Components (IPCs), an organized method of consolidation is applied, as depicted in the diagram on the left. This approach groups various IPCs into broader categories that represent the sections of the vehicle interior, such as the door, steering wheel, or Instrument Panel.

The visual diagram in the top right corner color-coordinates these groupings to their corresponding locations within a generalized vehicle interior. This visual representation aids in contextualizing where injuries are most likely to occur within the vehicle cabin, providing intuitive insights into the points of contact that are most significant in injury causation.

For the analysis, a comprehensive set of variables is extracted, including occupant demographics, crash specifics, and detailed injury information, such as AIS codes and rib fracture localizations. These characteristic variables serve as the foundation for a three-part analysis.

The first phase investigates injury prevalence, assessing whether there is a statistical difference in the frequency of injuries to certain thoracic regions between males and females, utilizing chi-squared analysis to determine significance.

Subsequently, the study then investigates injury causation, examining if certain IPCs are associated with injuries more frequently in one sex compared to the other. The final segment of the analysis concentrates on Rib Fracture Patterns, where the specific ribs fractured are analyzed to create a normalized frequency distribution to provide a visual comparison, illuminating potential differences in the pattern and

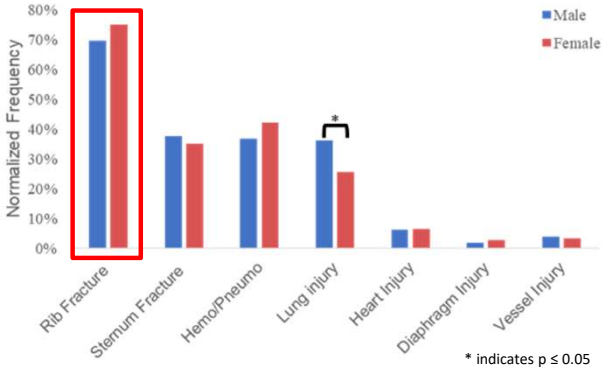
prevalence of rib fractures between males and females.

Results: Injury Prevalence

Occupant characteristics by sex.

Injury N (%)	Male (n=204)	Female (n=256)	Difference
Age (yr)	50.7 (21.1)	53.3 (19.4)	2.6
Weight (kg)	90.7 (23.0)	75.6 (22.2)	15.1*
Height (cm)	178.7 (7.3)	163.4 (7.2)	15.3*
BMI (kg/m2)	27.2 (5.4)	26.3 (5.3)	0.9
Delta-V (km/hr)	52.9 (22.8)	47.7 (19.7)	5.2*
Belted Status	150 (73.5%)	215 (84.0%)	10.5%*
Airbag Deployed	189 (92.7%)	231 (90.2%)	2.5%
Driver Position	179 (87.8%)	192 (75.0%)	12.8%*

* indicates $p \leq 0.05$



* indicates $p \leq 0.05$

Males involved in higher speed collisions and more likely to be unbelted and in the driver's seat.

860 AIS 2+ thoracic injuries sustained by 460 occupants

While **lung injuries more prevalent among males**, other injury categories were not significant.

Higher rib fracture occurrence observed in females despite lower crash severity/delta-V

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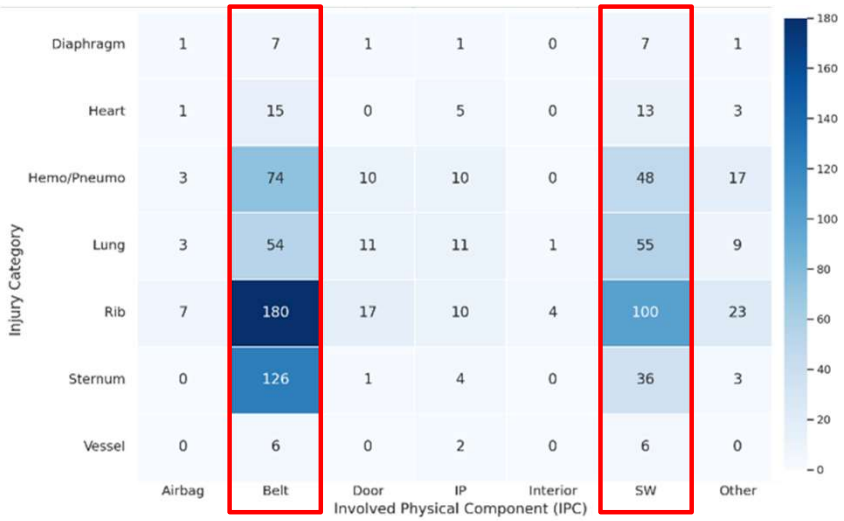
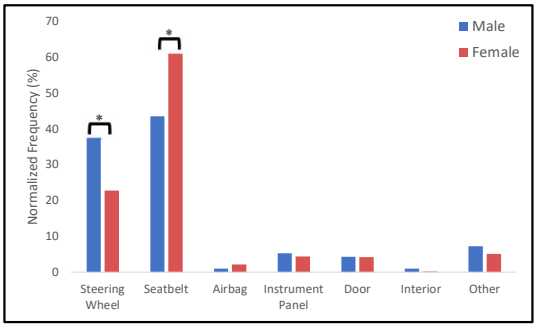
The results of the injury prevalence analysis reveal distinct characteristic differences between male and female occupants involved in motor vehicle collisions. Males generally presented with a higher average weight and height which is as expected. However, more notably, males were more frequently involved in higher severity collisions, as indicated by a greater change in velocity, or Delta-V, and were more often situated in the driver's seat. In contrast, females exhibited a higher rate of seatbelt usage.

When looking at injuries specifically, a total number of 860 AIS 2+ thoracic injuries were found sustained by 460 occupants. The chart in the top right distinctly that, while all other injury categories were not significant, a statistically significant higher incidence of lung injuries was seen in males than in females. A particularly intriguing detail, although not reaching statistical significance, is that females experienced a higher occurrence of rib fractures despite typically being involved in collisions of lower severity (highlighted by the red boxes), based on the average Delta-V. This outcome suggests that there may be underlying factors, potentially related to anatomical differences, safety design, or other variables, contributing to this discrepancy in injury patterns between the sexes.

Results: Injury Causation





- **Males had more injuries from the steering wheel.**
- **Females had a higher proportion of injuries attributed to seat belts.**

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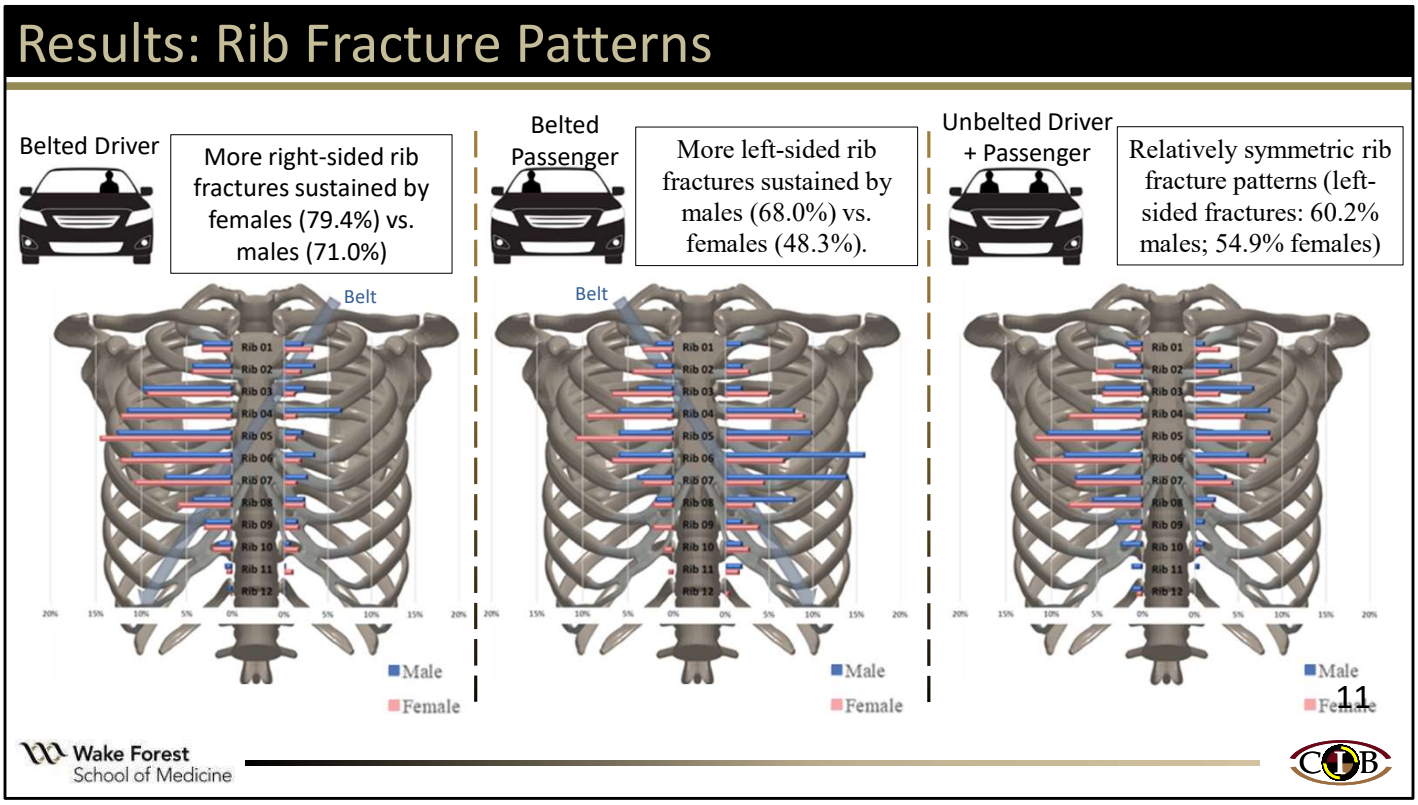
As we examine the causation of injuries from motor vehicle collisions, our analysis reveals two primary points of impact within the vehicle: the seatbelt and the steering wheel. This is visualized in the heat map to the left, which does not differentiate by sex, but categorically shows the frequency of injuries associated with various physical components of the vehicle's interior. The heat map highlights the steering wheel and the seatbelt as the predominant sources of injury across all injury categories, shown within the red boxes. These findings indicate that regardless of the type of injury sustained, these two components are most frequently involved.

When we dissect the data further, separating the instances of injury causation by sex as shown in the bar chart above, a pattern emerges. Injuries caused by the steering wheel are significantly more common among males. In contrast, a higher proportion of injuries among females are attributed to the seatbelt. These observations drive home the importance of incorporating a perspective of sex-specific differences into safety measures and highlight areas that may benefit from targeted safety enhancements to mitigate the risks for both male and female occupants.



When looking at the results of the rib fracture distribution analysis, we are presented with a visual representation of the normalized frequency of level-specific rib fractures between male and female occupants, overlaid on a representative rib cage. Blue bars indicate male-specific data, while red bars represent female-specific data, providing a clear sex-based differentiation in rib fracture occurrences.

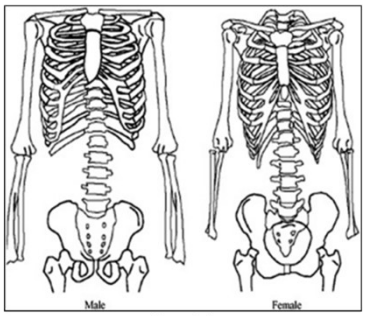
For the belted driver scenario, we observe a blue arrow illustrating the typical belt path which helps correlate the position of the seatbelt with the frequency and distribution of rib fractures sustained by occupants. Notably, there a higher incidence of right-sided rib fractures in females (79.4%) compared to males (71.0%). This could be indicative of differences in how seat belts interact with the anatomy of male and female occupants or possibly reflect variances in seating positions or postures during a collision.

When examining the belted passenger data, the arrow once again demonstrates the seatbelt path, this time the trend in rib fractures shifts. Here, left-sided rib fractures are more common in males (68.0%) than in females (48.3%). This suggests a difference in the mechanism of injury on the passenger side of the vehicle, which may be influenced by factors such as the point of impact or the direction of force during a collision.

In the case of unbelted drivers and passengers, the absence of the blue arrow removes the seatbelt from the equation, revealing a more symmetric distribution of rib fractures across both sexes.

Conclusion

Beuran et al.



Yang et al.

Sex-Specific Differences observed in thoracic **injury prevalence, rib fracture patterns, and injury sources** in frontal crashes.

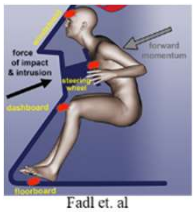
Anatomical, physiological, behavioral, and biomechanical factors play a significant role in susceptibility and response to thoracic injury.

Findings crucial for developing thoracic trauma **sex-specific prevention and management strategies.**

Highlights the **necessity for detailed data collection on injury causation** and mechanisms essential to identify influencing factors and improve outcomes.


NHTSA Crash Viewer

Sex-specificity should be considered in the development and assessment of vehicle safety systems and occupant protection.



Fadl et. al

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As we conclude our analysis, it's evident that sex-specific differences play a pivotal role in the prevalence and patterns of thoracic injuries sustained in frontal crashes. Our findings demonstrate that females tend to experience a higher rate of rib fractures, while males are more frequently subject to lung injuries, particularly those linked to impacts with the steering wheel.

The underlying reasons for these disparities are multifaceted. Anatomical and physiological differences between sexes, such as variations in muscle mass, bone density, and body structure, are likely contributors. Behavioral aspects, like differences in driving posture, and biomechanical factors also play a significant role in the susceptibility and response to thoracic injuries.

The significance of our study is profound, underscoring the necessity of developing thoracic trauma prevention and management strategies that are tailored to each sex. Furthermore, understanding these unique injury profiles enables us to propose more effective safety measures and interventions.

However, to advance our knowledge and improve safety outcomes, comprehensive data collection on injury causation and mechanisms is crucial. It is only through detailed and sex-disaggregated data that we can truly grasp the factors influencing injury outcomes for males and females.

Bringing all these points together, sex-specificity must be a fundamental consideration in the development and evaluation of vehicle safety systems and occupant protection measures. This is not just about enhancing safety in a general sense; it's about ensuring that our safety systems are robust and effective for

everyone. As we move forward, let us carry the insights from this study into the realm of automotive safety design, with the aim of protecting all occupants with the highest standards of care and precision.

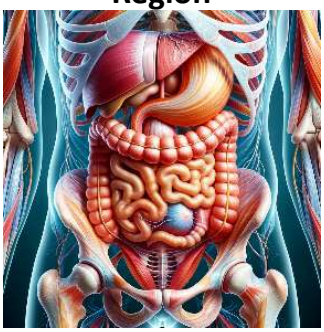
Future Work

Sex Differences in Chest, Thoracolumbar, and Abdominopelvic Injury Patterns and Causation in Frontal Motor Vehicle Crashes

Chest Region

Thoracolumbar Spine Region

Abdominopelvic Region



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Looking ahead, our commitment to deepening the understanding of sex-specific differences in motor vehicle injuries remains steadfast. We are starting a recently funded project entitled "Sex Differences in Chest, Thoracolumbar, and Abdominopelvic Injury Patterns and Causation in Frontal Motor Vehicle Crashes.“ through which we are broadening our scope to incorporate new data on sex differences in injury patterns and causation within distinct anatomical regions during frontal motor vehicle crashes. Our findings in the chest region have laid the groundwork for this expansion. Now, we're extending our focus to include the thoracolumbar spine and abdominopelvic regions, areas that are crucial for understanding the full impact of such incidents on the human body.

This expanded scope is essential for the development of vehicle safety systems that protect all occupants effectively and equitably. We look forward to sharing the insights gleaned from this project, with the ultimate goal of enhancing occupant protection and reducing the burden of injury in motor vehicle collisions. Thank you, and at this point, I will gladly take any questions.

Acknowledgements

Crash Injury Research & Engineering Network

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