Thoracic injury of Motorcyclists from Handlebar under Frontal impact in Thailand

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Abstract

Motorcycle accidents can lead to chest injuries that result in high mortality rates among motorcyclists. Among the different types of front collisions involving motorcycles, front chest impact with the side of a four-wheeled vehicle was found to be the most likely cause of severe thoracic injury amoung motorcyclists in this research. The study analyzed information collected in Phuket from October 2021 to May 2022. The most common harmful part and angle of impact were extracted from the analysis of accident simulation. The results from data statistical analysis significantly indicate that the side of a four-wheeler vehicle is the most influential area in causing more severe chest injuries in motorcyclists compared to other sites ($P<0.05$). Notably, a handlebar is one of the most significant parts that cause thoracic injuries. The most influential area of a four-wheeler vehicle and the common thoracic injury of motorcyclists from the harmful parts were used to investigate the effectiveness of possible protective gear. Thus, a chest protective gear can play a critical role in providing thoracic protection. Therefore, the FE human body models of motorcyclist were simulated under front chest impact based on collected data analysis. As a result, it was found that the 2 cm thick rubber of thoracic protective gear is effective only in a 5^{th} percentile female's chest from the left-frontal attack case. In addition, the findings of data analysis in this research can be used by policymakers and stakeholders to focus on reducing the impact of four-wheeler vehicle on motorcyclists and developing more effective protective gear to mitigate the severity of chest injuries in motorcycle accidents.

Keywords : motorcycle accident; thoracic injury; thoracic protective gear; in-depth data collection; accidental reconstruction

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1. Introduction

Motorcycle accidents are the main cause of deaths and injuries among overall traffic accidents throughout the world. According to the statistical data of World Health Organization (WHO), 945,000 people were killed in motorcycle accidents in 2018 [1]. Majority of these killed people were teenagers and young adults [2].

Although the incident of thoracic injury is not as high as soft tissue injuries, approximately 60 percent of thoracic-injured people could face death [3]. Indeed, the patient who has multiple thoracic organ injuries and rib fracture gain higher mortality risk because the thorax contains many vital organs [4].

Typically, severity of injury depends on impact velocity [5]. The impact direction also affects the level of thoracic injury [6]. However, different thoracic impact locations cause variation of organ injuries and traumatic configurations. The side of a four-wheeler vehicle with frontal collision of motorcyclist causes the most severity of thoracic injuries, compared with the frontal and rear collisions of four-wheeler vehicle [7]. Therefore, further study is needed to investigate the influence of impact locations and chest injury level in a step-through motorcyclist which is the most common motorcycle type found in Thailand.

As systematically reviewed, a handlebar of two-wheeled vehicle causes significant thoracoabdominal injuries in children, however, further evidence in adults is needed to clarify its effect on thoracic injuries [8].

Under the most current regulations, unlike helmet, chest protection gears were not mandatory by laws [9]. Some research works support the advantages of general protective clothing for motorcyclists in reducing injuries and length of stay in hospital [10]. Such research findings also suggest the effectiveness of the protective gear in thoracic injury protection.

Crushable foam is widely suggested for impact energy absorption in traffic accident. However, some studies showed that Ogden-Mooney Rivlin material can effectively protect the chest from severe blunt thoracic injuries [11]. While metal and ceramic textile composite are mainly suggested in acute chest penetrating injury protection [12], [13]. Despite widespread usage of crushable foam and convinced evidence in many research works, rubber material was studied to find out and support the pros and cons of Ogden-Mooney Rivlin rubber in crash worthiness [11]. Therefore, the objective of this research is to analyze chest injury severity in motorcyclist's frontal collision with the side of a four-wheeler vehicle. Furthermore, the part of vehicle that causes the most severity of motorcyclist thoracic injuries is investigated from the case selection. In addition, the rubber material is applied for the chest protective gear to evaluate its effectiveness based on human tolerance criteria [14].

2. Tools and definitions

In this research, STATA 17.0 program was utilized as the statistical tool for the sample size and data analysis. STATA is a statistical software that enables users to analyze, manage and produce graphical visualizations of data in many fields, for example biomedicine, economics, epidemiology, and sociology. In order to estimate the amount of sample size, the technique of retrospective cohort study was used [15]. Additionally, the PC-crash 10.0 and LS-dyna 4.0 program were used for multibody dynamics and Finite Element (FE) simulation respectively. A virtual human body model called Total Human Model for Safety (THUMS) are mainly classified in two genders for adults and children. Normally, THUMS [16] is used in FE simulation of human body under vehicle collisions. Therefore, the human body of motorcyclist under front chest impact with and without rubber of thoracic protective gear can be simulated to identify the thoracic injury from selected cases using THUMS.

Human thorax is the part of a human body that is situated between the neck and the abdomen and supported by the ribs, costal cartilages, and sternum. Human thorax contains various organs, for example, bony structure (ribs, sternum), lungs, heart, vessels and nerves [17]. Therefore, only some organs in human thorax of THUMS are included in this research due to the limitation of standard human tolerance criteria. However, the organs with uncertain reliable human tolerance are excluded. Human abdomen is defined as the anterior region of the trunk between the thoracic diaphragm superiorly and the pelvic brim inferiorly.

While human trunk means a part of human body which contains thorax and abdomen. Furthermore, chest deflection is defined as the compression distance of the chest, which is used to predict the risk of injury. A longer chest deflection indicates a higher risk of chest injury.

Measurement of thoracic injury severity and fatality prediction are evaluated using the AIS score as shown in **Table 1**. Abbreviated Injury Scale (AIS) score of 3 or higher is generally associated with high mortality, and it can be applied to assess injuries in all organs.

Table 1 AIS criteria for thoracic injury [18]

AIS	Injury Level	Description
1	Minor injury	-Contusion, closed-one rib fracture
2	Moderate injury	-Closed 2-3 Rib fracture -Closed multiple location, one rib fracture -Closed sternal fracture with stable rib cage -Dislocation, fracture spinous or transverse process t-spine -Minor compression fracture (<20%) t-spine
3	Serious injury, non-life-threatening	-Open rib fracture, comminuted rib fracture, displaced rib fracture -Unilateral hemo/pneumothorax, diaphragmatic injury -Intimal tear/minor laceration/thrombosis of subclavian or innominate artery
4	Severe, Life-threatening	-Flail chest -Bilateral hemo/pneumothorax, tension pneumothorax, massive hemothorax, tracheal fracture -Myocardial contusion

AIS	Injury Level	Description
5	Critical	-Visibly unstable chest, ruptured trachea, ventilator needed -Major aortic laceration, cardiac laceration
6	Non-survivable	-Dead at scene

3. Human tolerance criteria and injury mechanism

The assessment of chest deflection in Euro NCAP is divided into two criteria: lower and upper performance limits [19]. The lower performance limit indicates the criteria that can be minimally accepted, while the upper performance limit indicates the criteria that can be highly accepted. Therefore, the upper performance criteria of chest deflections are lower and result in fewer chest injuries than the lower performance limit. To provide clearer explanation of the performance limit, the following paragraphs provide more details.

The lower performance limit of the chest is the minimum score parameter used to predict a 50% risk of AIS score ≥ 3. Euro NCAP assessment establishes the human chest's lower performance limit as a deflection of 50 mm. A deflection value ≥ 50 mm indicates a 50% risk of AIS score ≥ 3. On the other hand, the upper (higher) performance limit is the maximum score parameter used to predict a 5% risk of AIS score ≥ 3. Euro NCAP assessment states that the human chest's upper performance limit is a deflection of 22 mm. A deflection value ≥ 22 mm indicates a 5% risk of AIS score ≥ 3. In this research, the correlation between chest deflection and AIS score was assessed according to the Euro NCAP assessment protocol.

The measurement of rib strain is used as an indicator of human tolerance criteria, which refers to the force per unit area within the ribs resulting from external forces or permanent deformation. It enables an accurate description and prediction of elastic and plastic behaviors. The human tolerance limit of rib strain for rib fracture detection is determined to be 0.3 based on existing theory [14]. Apart from chest deflection and rib strain, lung pressure is another indicator for thoracic injury. The pressure is exerted across the entire lung, including the airways. This is also influenced by both respiratory airflow and resistance as well as lung volume and compliance. If the lung pressure exceeds 10 kPa, it can predict the occurrence of pneumothorax [14].

To describe injury mechanism, fuel-tank collisions are the most common type of motorcycle accidents that result in thoracic injuries. When a rider collides with the motorcycle dashboard or other objects in the environment, it can result in impact force applying to the thoracic organs [20]. In some cases, shearing force can also increase the severity of thoracic injuries. However, the severity of thoracic and associated organ injuries is primarily dependent on the relative speed of the motorcyclist and the object, along with other health conditions and environmental factors.

Other types of collision typically do not cause direct thoracic injuries. Side collisions at lower location primarily cause injuries to the lower extremities of a rider or passenger, while those at higher location often result in head or upper extremity injuries. Nevertheless, some secondary impacts from head-on collisions can result in chest injuries, such as ground impact or subsequent collision with other objects.

4. Accidental data analysis

4.1 Procedure and parameters

To fulfill the objective of this research, raw data are firstly collected from accident scenes. Then, chest injury level in motorcyclists' front collision with a four-wheeler vehicle side and other locations can be analyzed. The relevant parameters recorded contain 1) Point of impact and point of rest from motorcycle, motorcyclists and four-wheeler vehicle 2) four-wheeler vehicle location of impact 3) Motorcyclist weight and height 4) Step-through motorcycle engine volume 5) four-wheeler vehicle engine volume 6) Vehicle deformations 7) Road types and characteristic 8) AIS injury score and injured thoracic organs by on-scene physician evaluation 9) Diagnosis and autopsy result 10) Types of collision

General data such as the average weight and height of the volunteers are reported after raw data collection. However, there are four distinct parameters to be selected for analysis such as 1) four-wheeler vehicle location of impact 2) motorcyclists' weight and height 3) AIS injury score and injured thoracic organs and 4) diagnosis and autopsy results. The others are utilized in completion of accident reconstruction.

Secondly, statistical analysis is performed to determine the location of impact and severity of thoracic injury through the sample size by using retrospective cohort study calculation. Such calculation with at least 50 cases is obtained from prevalence of outcome/exposure, prevalence of outcome/non-exposure, false positive and false negative values at 0.7, 0.3, 0.05 and 0.2 respectively. Accident reconstruction is then carried out using a multibody program to obtain incomplete parameters that were not initially collected. As a result, speed parameter and angle of impact from accident reconstruction analysis are identified independently.

Thirdly, numerical simulation using FE method is conducted through THUMS for harmful part of human being. This task is carried out to determine the most common configuration for each gender based on weight, height, front chest impact location, impact speed, and overall harmful part. Furthermore, the parameters from the multibody model reconstruction are selected from raw data to compare thoracic injuries in real samples that match each gender in the most common configuration with THUMS for human body simulations.

Finally, the effectiveness of chest protective gear is tested in the most frequent configuration for each gender in the FE simulation to predict a reduction in chest injuries of real cases. Thus, overall procedure for analysis is shown in **Figure 1**. Examples of collected data on-scene for accident reconstruction and analysis are shown in **Figure 2**.

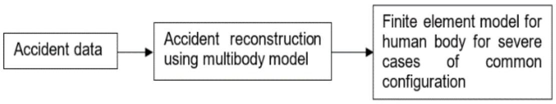


Fig. 1 Overall procedure of data collection and analysis

Fig. 2 On-scene investigation during emergency response

4.2 Population and sample size of accidental data

As previous calculation, at least fifty cases sampling was calculated based on retrospective cohort study statistical formula in statistical application. From on-scene investigation, eighty cases with inclusion criteria of this study for thoracic injury severity include three stipulations according to the four-wheeled vehicle side and other locations against a motorcyclist's frontal impact.

The first stipulation is 15-year-old or more among step-through motorcyclists. Principal diagnosis of the cases is thoracic injury from front collision as the second stipulation. For the last one, the litigant of a step-through motorcyclist is a four-wheeler vehicle. While the exclusion criteria in this initial data analysis consists of four stipulations. The first issue is pregnant motorcyclists. The principal diagnosis from the cases is not thoracic injury or is the thoracic injury from other mechanism than front collision as the second issue. For the third issue, the cases associated injuries with other than thoracic organ have AIS criteria 4-6 (life-threatened injury). The last issue are the cases with a pillion passenger. Thus, the procedure of case selection for impact analysis is shown in **Figure 3**.

The severity of injury is divided into 2 groups such as life-threatened (Thoracic AIS 4-6) and non-life-threatened cases (Thoracic AIS 1-3). Those groups were classified by on-scene physician evaluation.

Consequently, emphasizing only thoracic AIS, area of impact plays an important role which affects injury severity. Despite of the speed, four-wheeler vehicle side impact causes significantly severe chest injury than front and rear site of a four-wheeler vehicle (P-value < 0.05) with typical statistic null hypothesis acceptability of five percent.

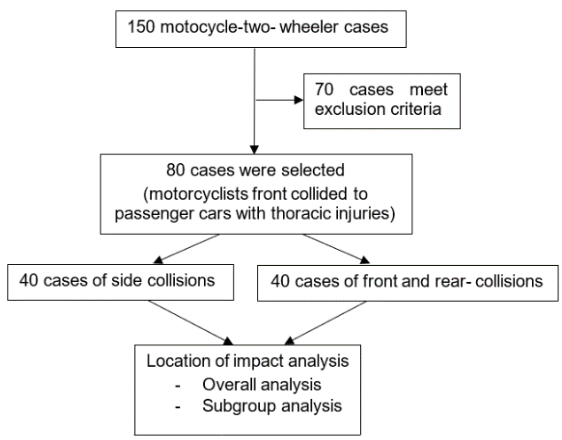


Fig. 3 Case selection steps for impact analysis

Table 2 Point of impact and injury severity analysis

Topics	Four-wheeled vehicle location of impact Side	Front and rear	Total
Life-threatened cases (AIS 4-6)	33	10	43
Non-Life-threatened cases (AIS 1-3)	7	30	37
Total	40	40	80

Topics	Point estimation	95% confidence interval
Risk difference	0.575	0.340-0.75
Risk ratio	3.3	1.89-5.75
Attribution fraction of exposure	0.70 (70%)	0.47-0.83
Attribution fraction of population	0.53 (53%)	N/A
		P-value < 0.05

Based on **Table 2**, it is observed that when a motorcyclist experiences a frontal impact with a car side, the risk of life-threatening injury is 3.3 times higher than other types of impacts. According to statistic parameters definition, attribution fraction expresses the real influence of an interested factor in specified studied sample, despite of other confounding factors such as age, gender, BMI, angle of impact, and type of road calculated by multiple logistic regression after raw data collection and multibody program simulation. The attribution fraction analysis in this study shows that the car side impact is one of the main risk factors which significantly contributes to the prevalence of life-threatening injuries, 70% and 53% in exposed cases and in population respectively.

Furthermore, the risk difference suggests that car side impacts result in more life-threatening cases of thoracic injuries than front or rear impacts with a four-wheeled vehicle. However, it is important to conduct further analysis to identify and control for confounding variables and other factors that may affect the prevalence of thoracic injuries such as the presence of harmful environmental objects at the scene such as bridges, barriers or else.

5. Accident reconstruction

5.1 Multibody and kinematic studies

The multibody simulation from PC-crash program was used to simulate events in all cases. The layout of road geometry obtained from the real scenes and human body geometry can be simulated as shown in **Figure 3-5**. Simulated results that were performed from the program were validated with the collected accidental data in order to analyze the location of impact**. Figure 3** and **Figure 4** show the distance in different variables among vehicle and human body from the real scenes and the program respectively. In this research, it is acceptable to have errors up to 10 percent in the program because the closest matches between the results of real scene position and multibody program simulation were found in this research(in this research, no simulations has an error more than 10 percent.) Therefore, the data collection, validation and reconstruction from the real scene can be illustrated step-by-step as shown in **Figure 3** and **Figure 4**. After the simulation of multibody program and real scene validation were conducted, VDO-based kinematic motion was monitored in each case to obtain 1) Definite angle of impact 2) Definite point of impact 3) Definite relative velocity of a motorcycle compared with a four-wheeled vehicle 4) Most possible kinematics of harmful part and chest impact location.

Fig. 3 Distance in different variables from real scene

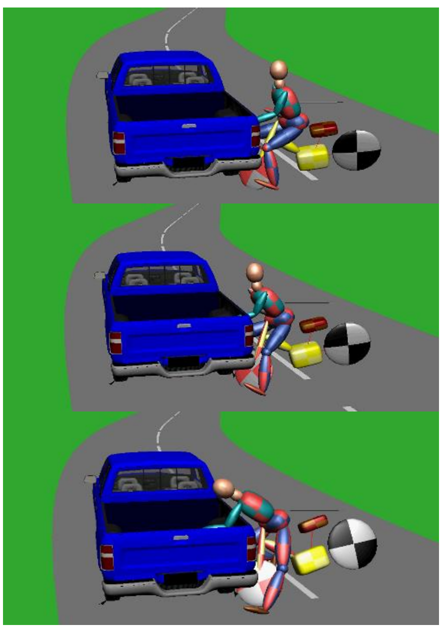


Fig. 4 Case validation in multibody program

In the case of front, rear, and side impact areas of four-wheeler vehicle, the trunk including the thorax and abdominal parts of motorcyclist typically hits or goes over the handlebar as shown in **Figure 4**. Such mechanism is followed by the body being thrown into other parts of the vehicle or the ground. At high speed, injuries to the head and neck usually occur as the second or third impact sequence. For the side impact of four-wheeler vehicle at low speed, the motorcyclist's body may come to a stop or fall at the point of impact or nearby. However, at high speed the body may be thrown and hit the car door or any pillar. Injuries to the face and neck are commonly associated with high-speed impacts. Furthermore, extended data can be obtained after kinematic analysis, such as the area of impact on the chest, the relative speed of impact, and the motorcycle angle of impact.

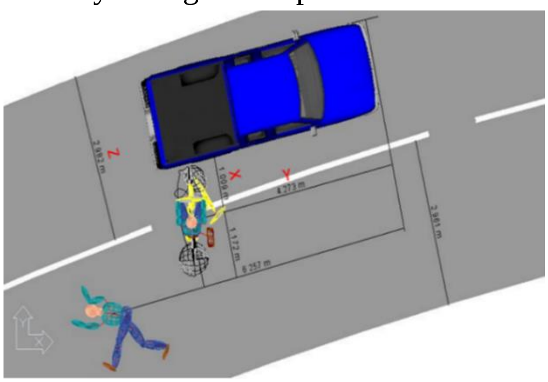


Fig. 5 Kinematic simulation of side impact

5.2 Kinematic analysis of motorcycle collision

In order to facilitate this research, the angle of impact gained from the multibody simulation in reconstruction are categorized into 5 groups in each location of impact. Each location of impact consists of frontal impact, rear impact, left side and right side. Furthermore, each group are divided by parameters of specific angle as shown in **Figure 6**.

After conducting various simulations in PC-crash 10.0 program along with kinematic study and analysis, it was found that the middle front chest is the most commonly affected position in male cases, while the left front is the most frequent configuration found in female cases. Side impact was found to be a common impact area in life-threatening cases. To have further analysis, only side impact cases was categorized into 3 zones of side impact as in **Figure 7**. Consequently, **Figure 8** reveals that zone B of the car side with angle group 5 is the most common configuration correlated with life-threatening cases with chest injury.

Table 3 Frequency of harmful parts and impact speed in life-threatened cases

Harmful part	**Applied Speed(km/hr.)***	**Frequency****
Motorcycle Handlebar	43.21	14
Car B-pillar***	41.25	12
Car A-pillar***	48	5
Car door	54.67	3
Rear panel	45	3
Car C-pillar***	57.5	2
Car bumper	60	2
Ground impact	60	1
Car bonnet	55	1
Total	46.26 (Average)	43

*Data obtained from kinematic simulation in multibody program

**Data obtained from the real life-threatened cases

***Car A, B and C-pillars are defined as number 1, 2, 3 in figure 7

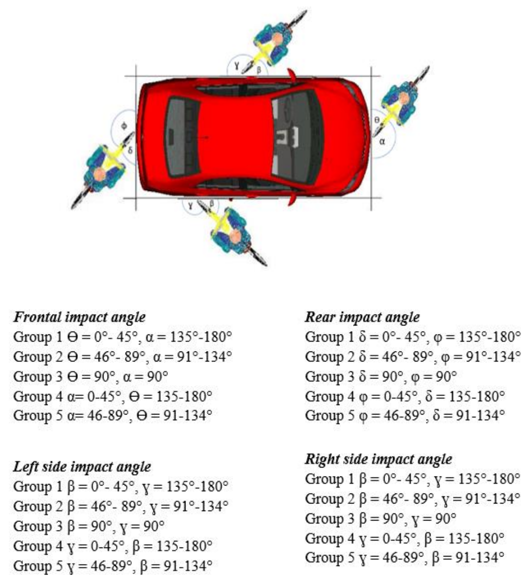


Fig. 6 Impact angle in each location

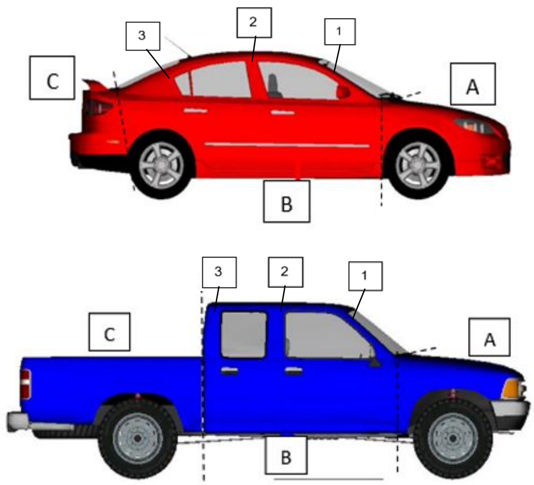


Fig. 7 Side impact zone and defined pillars in sedan and pick-up car

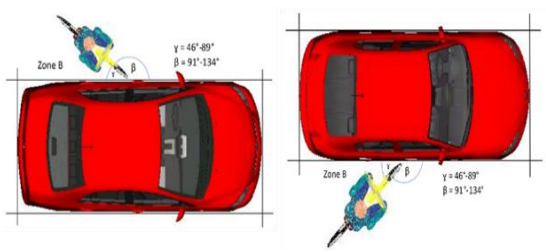


Fig. 8 Most common configuration of impact in life-threatened cases

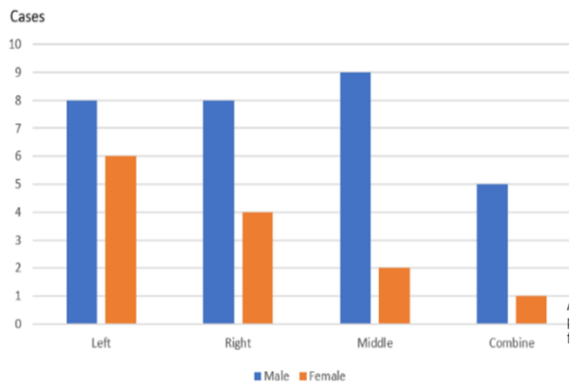


Fig. 9 Front chest's attacked position for life-threatened cases in each gender

In addition, after reconstructing 80 cases in PC-crash it was found that handlebars are the most common cause of chest injury, followed by B-pillar and rear panel of the car. The average speed in life-threatening cases involving handlebars was found to be 43.21 km/hr., which can be utilized in further experimental studies on thoracic protective gear. The reason why handlebars are the most frequent cause of thoracic injury in both overall and life-threatened cases is because they are present in all types of scenes, unlike other harmful parts that only occur in specific types of collisions as in **Table 3**. Furthermore, frequency of the front chest attacked positions in both males and females from simulation is shown in **Figure 9**.

6. Analysis of thoracic protective gear

6.1 *Simulation and model configuration*

To assess the protective gear, THUMS were used in FE simulation through usage of raw data and PC-crash simulation results as shown in **Figure 10**. The classification for THUMS simulation is based on motorcyclists' frontal impact to all locations of four-wheeler vehicle. Therefore, the number of each group are different from those in **Figure 3**. The average height and impact speed from only 43 life-threatened cases are determined for THUMS selection and impact condition in each gender simulation. The raw data were obtained from each gender's life-threatened cases to evaluate thoracic injury severity reduction from the protective gear. The common configuration in life-threatened cases were extracted for attacked positions of front chest in FE simulation.

In this research, the prototype of chest protective gear developed from Wei et al.' work [11] is used in effective evaluation for life-threatened cases. The model of chest protective gear is made of rubber material. In addition, the model of handlebar is made of typical metal material with density of 3.5 x 10^{-9} ton/mm^3, Poisson's ratio of 0.280 and Young modulus of 2.070 x 10^5 MPa. The model of handlebar is constrained in only one degree of freedom, which is moving towards from the front chest with speed of 43.21 km/hr. Besides, the actual handlebar can either twist (in left and right sides) or move towards-backwards from the chest. In order to simulate the twisted handlebar from real situation and PC-crash program, the handlebar model is controlled to move directly to the THUMS chest model. Hence, this configuration creates slightly different mechanism of injury. In the real cases of handlebar twisting condition, only the tip of the handlebar can attack motorcyclist' thorax and cause more localized injury. In this simulated case, the whole bar may attack the front chest and result in less localized injury.

To achieve the effectiveness of protective gear, LS-dyna program for FE simulation was used to simulate two sample cases, one for male and one for female, with AIS score equal to or over 4 as shown **Figure 11**. The average height and weight of each gender in real cases were measured to obtain suitable size of THUMS selection including the handlebar model as shown in **Table 4** and **Table 5**. A rubber size of 24.15 x 35.27 x 2 cm with density of 9.0 x 10 $^{-10}$ ton/mm3 and Poisson's ratio of 0.495 was modelled and applied to cover the front chest of THUMS at middle and left attacked positions with wearable application for male and female respectively. Consequently, human parameters such as chest deflections, ribs strain, ribs deflection, and lungs pressure can be measured and compared at each given speed for each gender.

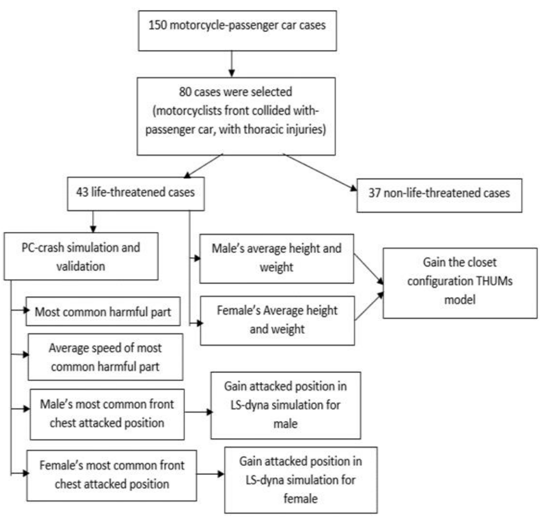


Fig. 10 Case extraction for protective gear analysis

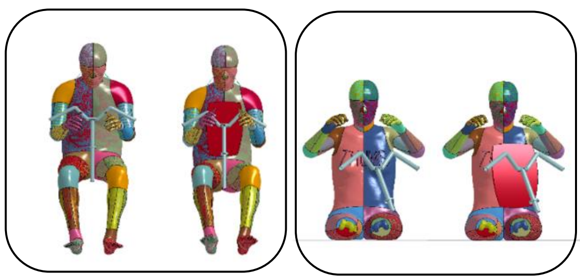
Table 4 Each life-threatened gender average height and weight

Gender	Average Height(cm	Average	Frequency
Male	170.53	68.50	30
Female	156.85	60.23	13
Total	166.39	66.0	43

Table 5 50th percentile male and 5th percentile female THUMS model weight and height

THUMS Model	Height(cm.)	Weight (Kg.)
50th percentile Male	175	77
5th percentile Female	152.4	49.9
Handlebar	-	5*

*Real measurement based on average weight and geometry of step-through motorcycle handlebar.



Male Female

Fig. 11 THUMS with and without chest protection

6.2 Chest injury and chest protective gear evaluation

In the real case, the height of motorcyclist matches the 50th percentile male THUMS model, resulting in the same handlebar-ribs level as shown in THUMS from the FE simulation. A 33-

year-old male (motorcyclist) with 175 cm height in this case was diagnosed with closed 4th and 5th ribs fracture both sides as shown in **Figure 12** (white arrows) with left massive hemothorax and great vessel injury from chest x-ray after colliding with a four-wheeler vehicle. The case was categorized as thoracic AIS 4 at the scene and then passed away soon after emergency resuscitation in the hospital. After the data collection and evaluation with PC-crash simulation, the handlebar was found as harmful part and the middle chest was attacked by the handlebar. While the simulated damage and actual injury are similar, sternal fracture did not occur in the simulation, making it possible to assess the effectiveness of chest protective gear. However, THUMS cannot be used to measure clinical diagnosis or temporary conditions, such as flail chest, real-time chest deflection, and deoxygenation. Furthermore, rubber protective gear from the simulation causes more pneumothorax in the 50th percentile male THUMS due to an increase in lung pressure from approximately 75 up to 83 percent that exceed 10 kPa of human tolerance limit, while decreasing overall rib strain and maximal rib deflection in the handlebar-attacked position. Rib deflections are measured by subtracting each rib's anterior-posterior position in caged ribs, and the float ribs (11th and 12th ribs) are not considered as shown in **Figure 13**. The rib strain contours with and without the protective gear also are measured as shown in **Figure 14**.

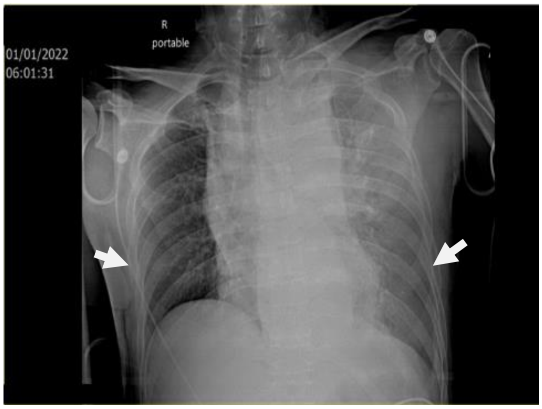


Fig. 12 Chest x-ray of male actual case

In comparing an actual female case to a 5th percentile female test (representing average life-threatened female configuration), the impact of handlebar at the left front chest produced similar results in the THUMS simulation. Since rib deflections in the 5th female were subtracted only from anterior left to posterior right sides (The impacted position and its opposite side), and float ribs were not considered in the model, the different rib deflection measurement in a female is obtained from different attacked position from a male. Therefore, the 5th percentile female's rib deflection that was measured from frontal (anterior) left and posterior right of rib cage is shown in **Figure 15**. The actual female case is a 52-year-old female motorcyclist with 155 cm height underwent motorcycle against four-wheeler vehicle collision, she was categorized to AIS 5 with hypovolemic shock and was early resuscitated at scene. However, soon after resuscitation, the patient was dead before reaching the hospital. The later autopsy result showed closed fracture of left 3rd -7th ribs with left hemopneumothorax. Similarly, after data collection and evaluation with PC-crash simulation, the handlebar was found to be harmful part and the middle chest was attacked by the handlebar. However, left 6th rib fracture was not observed in the THUMS simulation. Despite the intact 6th rib cortex, the 8th-9th rib fractures were detected. Both lungs pneumothorax was found in the THUMS simulation through the measured lung pressure that reduced from approximately 87 to 77 percent of exceeding human tolerance limit of 10 kPa with and without the protective gears respectively. And the rib strain contour is shown in **Figure 16**, while only left lung pneumothorax was diagnosed in the actual case. However, hemothorax and hypovolemic shock cannot be obtained from the simulation.

In the 50th percentile male THUMS, applying the rubber chest protective gear leads to increase in lung pressure and some rib deflection due to load distribution, while decreasing overall rib fracture tendency as shown in **Figure 13** and **Figure 14**. The more localized the force acting on the ribs, the greater the tendency for specific rib fractures. In contrast, the 5th percentile female was tested only for left front chest impact, and the rubber chest protective gear reduced overall rib strain, both lungs pressure and maximal rib deflection, hence decreasing overall rib fracture tendency.

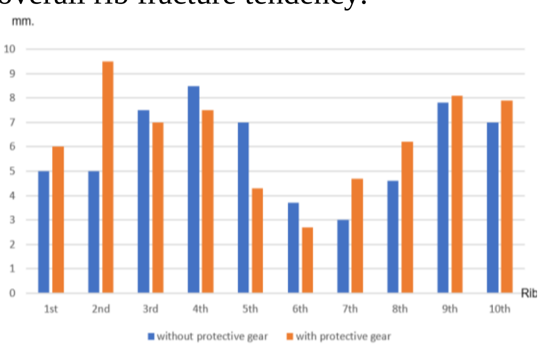


Fig. 13 50th percentile male's left ribs deflection

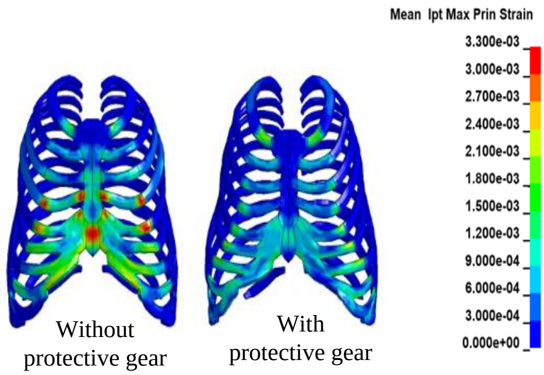


Fig. 14 50th percentile male's rib stain without and with chest protective gear

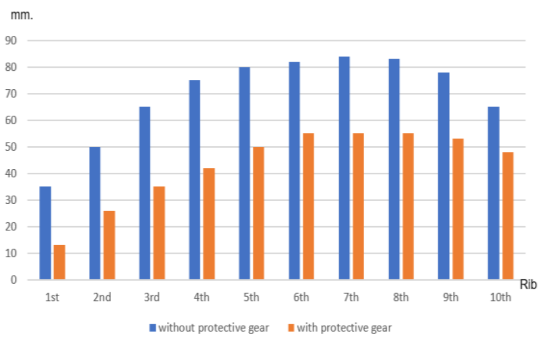


Fig. 15 5th percentile female's rib deflection

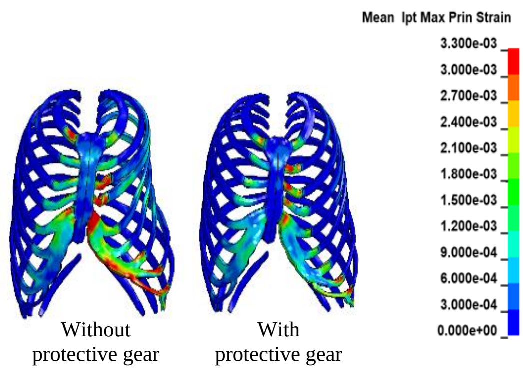


Fig. 16 5th percentile female's rib stain without and with chest protective gear

As shown in **Figure 13** and **Figure 14**, the THUMS simulation in 50th percentile male showed that rubber chest protective gear decrease left 3rd, 4th, 5th, 6th ribs deflection but increase other left ribs' deflection. For the 5th percentile female, the results showed that rubber chest protective gear decreases all rib deflections. Especially, the 2nd -5th rib deflections are decreased from more to less than the lower performance limit (less than 50% risk of AIS score ≥ 3) and the 1st rib deflection is decreased from more to less than the upper performance limit (less than 5% risk of AIS score ≥ 3).

7. Discussion and Conclusion

The findings of data statistical analysis show that the side of impact and speed of the collision are the most significant factors in determining the severity of chest injury in motorcyclists' front impact. In addition, the handlebars are the most frequent cause of thoracic injury in both overall and life-threatening cases in kinematic simulations from multibody program. Other factors, such as age, gender, BMI, angle of impact, and type of road, do not significantly affect the severity of chest injury. Further research is recommended to analyze different directions of impact on thoracic injury severity.

In THUMS model, the handlebar was modeled using the properties of a steel bar. However, in real step-through motorcycles, the handlebar is wrapped by rubber coverage. Therefore, results from FE simulation may indicate more injury than the real handlebar. Thus, it should be modelled in future simulations to obtain more realistic results and recommendations for the use of force-absorbing materials in chest protective gears. Additionally, the design, availability, and applicability of chest protective gear need to be considered.

The use of rubber chest protective gear can reduce rib fracture in the male case but may increase lung pressure due to more impact force distribution and increase most male's rib deflections. The increment of lung pressure under pneumothorax causes lowering body gas exchange, which is more fatal than rib fracture [21]. In the female case, rubber chest cushion reduces all analyzed factors, including ribs fracture, both lung pressure, and all rib deflections. The differences of real female case and THUMS models might come from different localized impact load applying to the chest. However, different physical factors and collision types may result in different outcomes. Therefore, future studies should consider different situations and collision types to create more functional crash worthiness.

Finally, confounding human body factors could not be analyzed in this research due to the fixed properties of THUMS. The approximation was compared to the closest configurations in the real case. However, factors such as bone mass, muscle thickness, underlying conditions, sex hormones, and drug use in actual cases need to be considered in future studies.

8. References

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