Powered Two-Wheeler Rider Thoracic Impact Loading in Crashes with the Side of Passenger Cars: Literature Review and Human Body Model Validation

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Abstract Globally, powered two-wheeler (PTW) riders constitute a vulnerable road user group. This study aims to enhance the understanding of thoracic loading experienced by PTW riders in one of the most common crash configurations, PTW front to passenger car side (PFCS) impacts. A scoping review of the literature identified impact parameters describing common thoracic loading in terms of direction, location, distribution, and magnitude.

Four experimental hub and bar post-mortem human subject (PMHS) test series, covering some of the identified variations in thoracic loading, were selected to validate the thorax of the SAFER human body model (HBM). The SAFER HBM demonstrated fair kinetics and kinematics biofidelity for frontal and oblique hub impacts and poor to fair biofidelity for the bar impacts. However, the SAFER HBM can accurately predict the rib fracture risk estimated from the PMHS tests.

The findings demonstrate the potential of current HBMs to represent PTW-specific thoracic loading and support development of PTW rider safety systems in upright PFCS impacts. It also highlights a need for novel PMHS tests, in particular ones where the thorax is loaded above mid sternum and preferably including a vertical force component.

Keywords Human body model, literature review, powered two-wheeler, thorax, validation.

I. INTRODUCTION

Globally, vulnerable road users (VRUs), pedestrians, bicyclists, and powered two and three-wheeler users, account for a majority of road traffic fatalities [1]. In particular, powered two and three-wheeler users represent the largest portion of fatalities among VRUs, comprising 28% of all global road traffic deaths in 2016, while reaching as high as 43% in Southeast Asia [1]. Compared to other VRU groups and vehicle occupants, powered two wheelers (PTWs) is the only road user group with an increasing number of fatalities in the period 2010-2019 [2]. Today, PTWs are the most common mode of transportation in countries such as India and Thailand [3],[4]. In regions such as Europe and the US, where the proportion of PTWs in the vehicle fleet is lower, the number of registered PTWs is increasing [5].

Common PTW crash scenarios include single- and multi-vehicle crashes, in roughly equal proportions worldwide [6-11]. In single vehicle crashes, impacts with road-side objects or the ground are common scenarios [10],[12]. In multi-vehicle crashes, where passenger cars are the most frequent collision partner [7],[13-16], one of the most common scenarios is different angled impacts of PTW front to passenger car side (PFCS) [6],[8],[11],[12],[14], often leading to severe thoracic and head injuries for the PTW rider [17-19]. Historically, significant effort has been made towards reducing head injuries for PTW users [20], perhaps most notably by the development of helmets and mandatory helmet laws. For example in California, the proportions of severe head injuries to other injuries was reduced from 61% to 43% after the introduction of a law mandating helmet use [21]. However, no personal protective equipment for the thorax with similar demonstrated effectiveness exists [22],[23]. To enable the development of effective thoracic injury countermeasures for PTW riders, an increased understanding of the thoracic injury mechanisms is needed.

Injury assessment for PTW riders have traditionally been performed using physical or Finite Element (FE) Anthropometric Test Devices (ATDs). ATDs used in PTW applications, such as the Hybrid III [24],[25] or the

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modified PTW-version Motorcyclist Anthropomorphic Test Device (MATD) [26],[27], are developed for frontal specific crash directions measuring the longitudinal chest compression to estimate thorax injury risk [28],[29]. Most likely the ATDs operating range is not applicable for the potentially damaging, and complex nature of PTW accidents. Another potential rider substitute is a detailed FE Human Body Model (HBM). FE-HBMs are omnidirectional by design with a more biofidelic representation of the human anatomy, which allow for injury risk assessment at tissue-level. One such HBM is the SAFER HBM featuring a generic rib cage, based on statistical shape models, that has previously been validated for kinetic, kinematic, and rib strain responses, ranging from single rib to complete ribcage, in various car occupant impact configurations [30-32].

HBMs have primarily been developed and validated to replicate the in-crash responses of car occupants and pedestrians. Despite the lack of consideration for PTW-specific validation, HBMs have recently been introduced in PTW rider applications, to evaluate the protective effect of different passive safety systems [15],[22],[33-36]. For example, the validation of the Global Human Body Models Consortium (GHBMC) thorax model [37] for PTW applications, was briefly addressed in the PIONEERS project [38]. In the project it was assumed that the thorax loading of car occupants in crashes was similar to that of PTW riders in crashes. Therefore, the existing validation of the HBM was considered sufficient. However, no further justification of why the selection of available load cases, anterior-posterior rib bending, point loading of the denuded ribcage, omnidirectional pendulum impact (frontal and lateral), and table-top, represent the thoracic loading for PTW riders were given.

Therefore, this study has two aims. First, to systematically map available research through a scoping review of the literature to provide an enhanced understanding of PTW rider-specific thoracic injuries by identifying impact parameters describing common thoracic loading experienced by PTW riders in upright PFCS impacts. Second, to identify thoracic validation load cases relevant to the identified thoracic loading scenarios and validate the SAFER HBM thorax by means of these experimental tests.

II. METHODS

This section is divided into two parts. In the first part, an overview of the method used for a scoping review of the literature is described. In the second part, the experimental validation tests and corresponding simulation setups are presented.

Literature review

To summarise the research related to thoracic loading in PFCS impact configurations, a scoping review of the literature was conducted based on the 22-item Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines and four-phase flow diagram (Fig. 1) [39].

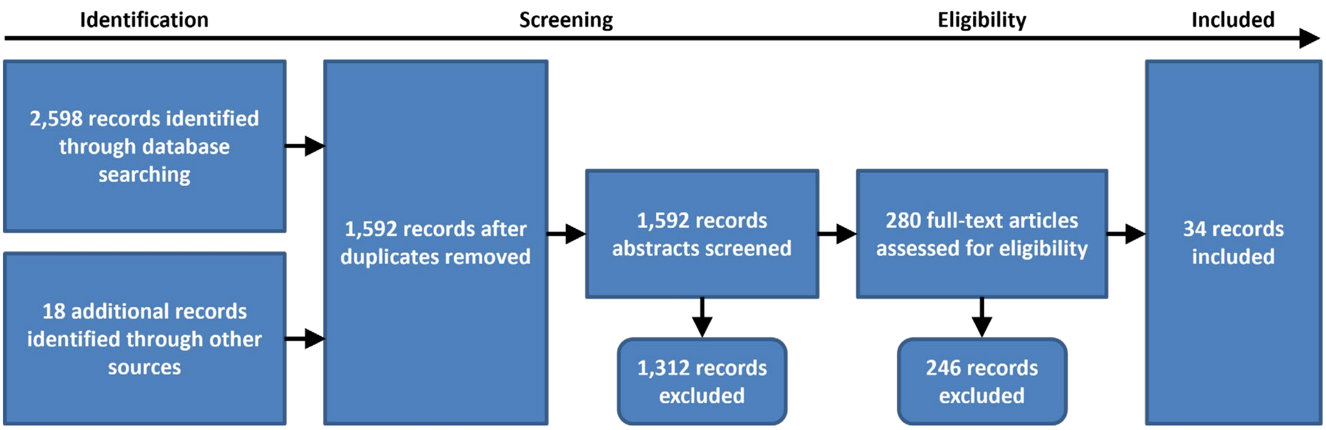


Fig. 1. Information flow through the different phases of the scoping review described using the four-phase PRISMA flow diagram [39].

Publications were identified by searching four electronic databases - Google Scholar, Scopus, Web of Science, and PubMed, with an English language restriction. The search strategy was developed by extracting key search terms from six papers representing epidemiological, simulation, and experimental based studies. The six studies [10],[13],[18],[40-42] were chosen because they represent methods and results central to the investigated topic. The key search terms were combined into a common query and manually translated to each database's specific search syntax and operators. It was controlled that the six chosen papers were included in the pooled sample of publications. The electronic search strategy for the different databases is available in Appendix A.

Since Google Scholar lack an advanced search syntax, Harzing's *Publish or Perish* software v8 [43] was used to facilitate the Google Scholar search. Synonyms in the search query were reduced to not exceed the limit of 256 characters and the query was applied to title, abstract and full-text content. For Google Scholar, the top 500 records, ranked by relevance were included. The search was conducted on the 9 January 2023, for all databases. Additional studies recommended by project partners and European Union funded projects focusing on PTWs were, regardless of language restrictions, also included as supplementary records.

The study selection was performed sequentially as illustrated in Fig. 1, starting with an import of the pooled sample of publications into EndNote 20.5 [44], next removal of duplicates, followed by an abstract screening, and finally a full-text eligibility check was performed, provided that the publication was not eliminated in the previous abstract screening step. To be included in the final sample, a publication was required to satisfy at least one inclusion criteria and none of the exclusion criteria presented in Table I. The full-text eligibility check used the same inclusion and exclusion criteria as for the abstract screening. The entire screening and eligibility process was performed by the main author. Finally, no publications were excluded based on quality assessments. Further, the full-text documents of twelve articles could not be retrieved.

The data extraction process involved categorising verbatim text into five categories: (i) In-crash kinematic description, (ii) loading direction (iii) injury source, (iv) thoracic loading location, and (v) magnitude of loading. The categorized text was then synthesised to align with the research aim, utilizing a narrative format commonly employed in the eligible studies.

TABLE I
LITERATURE REVIEW INCLUSION AND EXCLUSION CRITERIA

Inclusion criteria	*Exclusion criteria*
• Epidemiological analyses stratified depending on multi-vehicle impacts and thorax. • Accidentological analyses stratified depending on PFCS impacts and thorax. • Multibody-, FE-based simulations, or physical crash tests investigating upright PFCS impacts describe either kinematics or loading with respect to the rider in general, or thorax in particular. • General thoracic injury mechanisms and descriptions with an association to PFCS impacts.	• The investigated PTWs are an electric pedal-assisted vehicle or could not be differentiated from one. • An explicit focus on riders younger than 18 years old. • An explicit focus on pillion riders or the influence of their presence in a crash. • Involvement of non-wearable restraint systems altering kinematics, such as airbags.

Thoracic Validation

The thoracic validation was based on four experimental test series chosen because they encompass part of the thoracic loading scenarios identified in the literature review. The four loading configurations include a frontal midsternal hub impact [45], a frontal thoracoabdominal bar impact [46], frontal thoracic bar impacts at three different heights [47], and oblique thoracoabdominal and thoracic hub impacts at three different impact speeds [48]. Detailed parameters for each loading configurations are provided in Table II. The thoracic response of the SAFER HBM v10.0 [49], representing a 50^{th} percentile male (77 kg, and 175 cm), and specifically its appropriateness to predict thoracic loading experienced by PTW rider, was evaluated by means of these load cases.

Predicted responses were compared both qualitatively and quantitatively to unscaled kinetic and kinematic responses from the four experimental series except for the frontal midsternal hub impact, where normalised data was used to develop the response corridors [45]. The quantitative evaluation used the OpenVT Python implementation of the ISO/TS 18571:2014 standard [50] to assess the biofidelity of the simulated force vs. time histories for all configurations except the frontal midsternal hub where no time histories were available. The

ISO/TS 18571 ratings were calculated using both individual post-mortem human subject (PMHS) signals and average response signals obtained by averaging all individual PMHS signals for each test respectively. The evaluation interval was set to 0-60 ms for all comparisons to include both the loading and unloading phases.

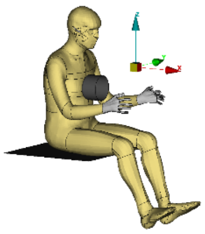
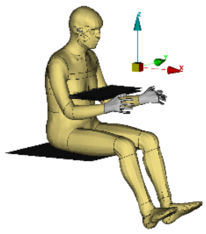
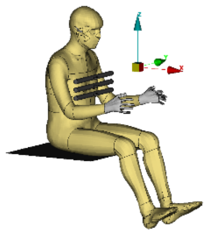
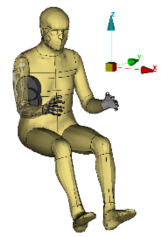
The rib fractures risk was predicted using a probabilistic framework [51], where the peak first principal strains in the neutral layer, from each rib's cortical bone was used as input. The predicted fracture risk for the SAFER HBM was compared to the number of rib fractures recorded in the PMHSs for the frontal thoracoabdominal bar impacts and oblique thoracoabdominal impacts.

The force was measured as the contact force in the impact direction between the impactor and HBM thorax. The PMHS displacement on the non-impacted side was computed as the averaged displacement of all nodes in a 30x30mm skin region, to mimic the adhesive zone of a photo target. Deflection was defined as the displacement between the rigid impactor and the flesh on the non-impacted side of the model, along the impact direction.

The nominal posture of the SAFER HBM was used in all simulations, although rotated 22° around the nominal Y-axis to mimic the straight back posture perpendicular to the loading direction that was used in the PMHS tests. Gravity was applied in all loading configurations except for the oblique impacts, and the SAFER HBM was given 350 ms to settle on a rigid platform. For the oblique impacts, gravity and the platform were excluded since the experimental test series were conducted using PMHSs suspended upright by their arms. However, using the nominal posture of the SAFER HBM was still considered to be an acceptable simplification since the organ volumes and their positions have been shown to be mostly unaffected by posture [52]. The impactor-to-HBM and platform-to-HBM contacts used static and dynamic friction coefficients of 0.3. All simulations were performed using 32 cores and LS-DYNA MPP R9.3.1 (ANSYS Livermore Software Technology, California, United States).

TABLE II

IMPACT CONFIGURATIONS FOR THE KINETIC AND KINEMATIC VALIDATION

				
Load case	Frontal midsternal hub [45]	Frontal thoracoabdominal bar [46]	Frontal thoracic bar [47]	Oblique (30°) thoracoabdominal and thoracic hub [48]
Impactor	Ø 15.2 cm, 1.2 cm edge radius, 23.4 kg	Ø 2.5 cm, 47 cm in Y, 48 kg	Ø 3 cm, 40 cm in Y, 25.8 kg	Ø 15 cm, 1.2 cm edge radius, 23.4 kg
Alignment of impactor centre	Y: Mid sagittal Z: 4^{th} intercostal connection to sternum	Y: Mid sagittal Z: T11 vertebrae	Y: Mid sagittal Z: Three locations; 4th intercostal connection to sternum (middle), ΔZ=±50 mm (lower/higher)	X: Through torso CoG Z: Two locations relative centroid of sternum; ΔZ=-75 mm (thorax), ΔZ=-150mm (abdomen)
Initial velocity [m/s]	6.7	6.1	2.4	Thorax; 4.4, 6.5, 9.5 Abdomen; 4.8, 6.8, 9.4

III. RESULTS

The first part of the results section presents the findings from the 34 papers collected through the scoping review of the literature. The findings in terms of kinematics, loading location, distribution, direction, and magnitude have then been summarised as a set of impact parameters to guide the selection and future development of relevant PMHS tests for validation of the thorax of HBMs. Lastly, the validation of the SAFER HBM is presented for a selection of four loading configurations that closely corresponds to the impact parameters identified in the literature review.

Findings from the Literature Review

The majority of studies on rider kinematics in PFCS impacts have been conducted using physical full-scale crash tests with ATDs, which are represented in twelve of the included studies reporting on detailed rider kinematics (Appendix B). In addition, multibody simulations have been employed in nine studies, while FE simulations have been used in five studies. Physical full-scale tests with PMHSs are rare, represented in only two studies. The impact scenarios studied include perpendicular and angled impacts of the PTW front to various locations of the side of either moving or stationary cars.

In-crash Kinematics and Loading Direction

All studies investigating perpendicular PTW front to *stationary* car side impacts report similar global rider kinematics. As the PTW decelerates against the car, the unrestrained rider slides forward relative to the seat until the forward motion of the rider's lower body is restricted by the PTW or the opposing car [18],[24],[26],[41],[53-59]. The constrained lower body, in combination with the forward momentum, initiates a forward pitching motion of the rider's upper body [13],[24],[41],[53-61].

Overall, the body of literature suggests that for perpendicular PTW front to *stationary* car side impacts, the thorax primary loading direction is anterior-posterior [56],[62]. In some cases, the main load vector has been identified to have secondary superior-inferior or inferior-superior components, with the direction of the vertical component seeming to depend on the amount of upper body pitching to vertical lift caused by lower body constrictions [13],[27],[54],[56],[62]. Knowledge on the curvature of the injury source is also needed to complement the analysis on secondary force components, since the striking objects' radii, and orientation relative to the thorax, have been shown to contribute to the loading direction [63].

The studies on PFCS impacts report the addition of yaw rotation to the global rider kinematics for angled or perpendicular impacts with *moving* cars [13],[18],[24],[41],[55],[56],[61]. This yaw rotation can occur as the PTW's front wheel turns upon impact in the opposing car's direction of travel, causing the handlebars to follow [56]. The resulting uneven loading on the rider's legs and hips from the PTW further induces upper body yaw [56]. Increased yaw has been shown to result in less pitch and less upward motion of the rider, redirecting the rider's momentum laterally from the original PTW direction of travel [13],[18],[41],[55],[56].

The amount and relative proportion of pitch and yaw motion depend on parameters such as the two vehicles velocity and the PTW impact angle [24],[56],[64]. As a result, the primary loading direction to the thorax can range from anterior-posterior in pitch-dependent impacts to oblique in pitch-yaw-dependent impacts and even pure lateral in yaw-dependent impacts [13],[18],[24],[41],[55],[56],[61],[62].

Injury Source

The lateral side of the thorax impacts the car's side structure in yaw-dependent impacts, but the actual impact site depends on the PTW's impact location relative to the car. In pitch-dependent impacts, thoracic contact above the car's lower side window edge is more common than impacts below [65]. When directly impacting the passenger compartment, the rider's impact height with respect to the car determines whether the head or the superior-anterior part of the thorax is the first body region to contact the roof rail [27],[54],[64],[66-68]. Lower sections of the car can also be impacted, as observed when the rider has an initial lateral lean prior to impact, resulting in the thorax impacting the lower portion of the car's side structure including the front fender area [57]. To mimic the loading to the thorax in a component test setup, impacts with rigid cylinders ranging from 5-25 cm radii has been suggested as idealised injury sources [36],[63].

The handlebars, typically with a diameter between 2-3 cm [69], are the most commonly reported PTW structure causing thoracic injury, with the rider subjected to oblique impact loading due to torsion of the handlebars initiated by the deflection of the front wheel [70]. PTWs with a step-through geometry can also cause posteriorly directed handlebar loading as no superior component to the rider's trajectory is introduced prior to handlebar contact because of the absence of pelvis interactions with the fuel tank [13],[18],[24],[26],[71]. Although only reported in one study and described as a rare event, piercing injures to the thorax can also occur and is caused by loading from the handlebar ends [72].

Several parameters determine the rider in-crash kinematics. It has been shown that the rider posture, seat height, PTW type, and PTW impact point relative to the car significantly influence the rider in-crash kinematics and, ultimately, the thoracic injury source [18],[24],[58],[59],[66],[67]. In summary, the literature review identified both curved surfaces (A-pillar, roof rail, handlebar, etc.), and flat surfaces (bonnet, side windows, doors, etc.) as injury sources in upright PFCS impacts [12],[13],[19],[24],[26],[27],[55],[58],[62-64],[66],[72-74]. These represent more or less concentrated thoracic loading distributions possible to impact in different orientations relative to the thorax.

Thoracic Location

The in-crash kinematics of PTW riders were described to mainly involve pitch and yaw motion, or a combination thereof. Consequently, this will result in loading to both the anterior, oblique, and lateral regions of the thorax. Supporting this is a parametric multibody study, that found the anterior and lateral thoracic regions to be the most frequently impacted out of 15 analysed body regions, making up 12.7% (anterior thorax) and 12.2% (lateral thorax) of all simulated impacts against the car [18]. Another multibody study also reported on the most commonly impacted thorax regions and found impacts frequently clustered around the sternum area, especially for crashes with a conventional motorcycle geometry, whereas the superior lateral part of the thorax had a high impact frequency independent of whether a conventional motorcycle, or a step-through PTW geometry, was used [40]. This is in line with a clustering of shoulder-region injuries argued to be caused by loading to the superior lateral thorax region, reported in an in-depth accident data study [42].

Loading Magnitude

Knowledge on the magnitude of the loading is required to complement the description derived from the in-crash kinematics in terms of loading direction, distribution, and location. However, no studies based on accident data found in the scoping review have collected and reported impact speed with regards to both thoracic injury severity and crash configuration. Therefore, physical testing and simulation based data are the sources available for an evaluation of the load magnitude to the thorax for PFCS impacts.

For physical perpendicular PTW front to stationary car side tests with PTW impact speeds of 32 and 48 km/h, ATD peak chest accelerations ranged from magnitudes below 40 G for flatter and more compliant car structures (door/window 34 G, bonnet 18-38 G), to magnitudes above 55 G for more curved and rigid structures (A-pillar/roof rail 56 G, top edge of front fender 62 G) [57]. In accordance with these results is a PMHS test in the same crash configuration with a PTW impact speed of 40 km/h, conducted by [13], where thorax accelerations of 60 G were registered for a chest to B-pillar impact, preceded by a head to roof-rail impact. However, if a yaw component was introduced through a 45° impact angle between the PTW front and car side, [64] found using multibody analysis, that the peak accelerations increased from 30 G to 90 G because of the more direct lateral impact to the thorax compared with the perpendicular pitch-dominated impact. In general, thoracic load magnitude in upright PFCS impacts are reported to be a result of the impact speed of the PTW, together with the stiffness and the shape of the injury source [17],[40],[63].

Parameters Describing Thoracic Loading in Upright PTW Rider Impacts to the Side of Passenger Cars

The findings from the reviewed body of literature are condensed into four fundamental impact parameters, location, distribution, direction, and magnitude, describing the general loading scenarios experienced by PTW riders in upright PFCS impacts. The impact parameters are further described in Table III.

All identified impact parameters except magnitude are readily translated from rider-to-object to PMHS test or HBM simulation setups, commonly seen in object-to-rider configurations. The difficulty in defining the magnitude in object-to-rider setups comes from the translation of the effective mass of the rider involved in the loading in relation to the impactors distribution and velocity [22]. Because of this, no general test-specific recommendations on load magnitudes can be provided. Instead, the reader is, in accordance with the recommendations in [22], suggested to, for each load condition, select a combination of mass and impact velocity, that give the injury severity of interest.

Four experimental PMHS test series incorporating thoracic impact parameters presented in Table III were selected to be used for validation of the SAFER HBM. The load location in these tests incorporates frontal to oblique loading locations with a combination of 2.5 to 3-cm-diameter curved and 15-cm-diameter sized flat load distributions in anterior-posterior to oblique loading directions with load magnitudes resulting in rib fractures. In the following section, the results from the validation of the SAFER HBM using these four experimental test series are presented.

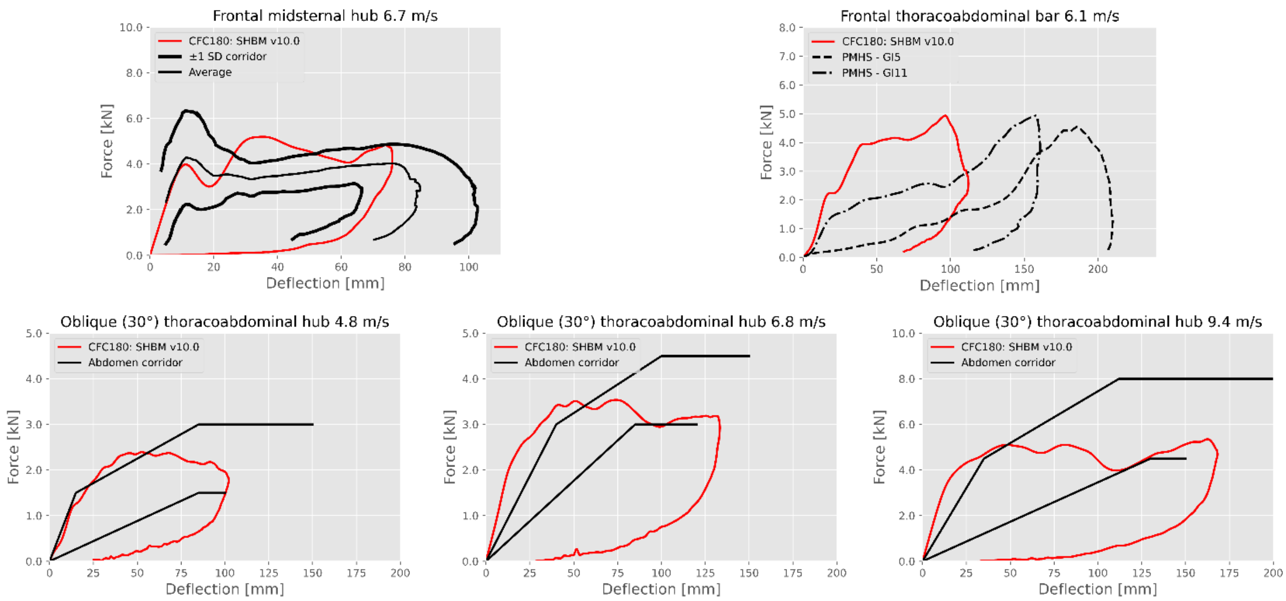
TABLE III

IMPACT PARAMETERS DESCRIBING THE THORACIC LOADING EXPERIENCED BY PTW RIDERS IN UPRIGHT IMPACTS TO THE SIDE OF PASSENGER CARS

Parameter	Description
Loading location	Transverse plan: Anterior to lateral parts of the thorax Coronal plane: Entire rib cage region
Loading distribution	Flat and curved injury sources Small (Ø2-3cm), middle (Ø10-20cm), and large (Ø50cm) object diameter
Loading direction	Primarily in anterior-posterior to lateral direction with either superior or inferior components
Loading magnitude	Dependent on loading distribution and studied injury severity level

Thoracic Validation

The predicted frontal midsternal hub response matched the experimental corridor except in 25 mm (between 25 and 50 mm of deflection) where the response was above the upper boundary (Fig. 2). The predicted frontal thoracoabdominal bar response matched the peak force magnitude of the individual signals. However, from 10-75 mm deflection, the predicted response was higher than in the tests with a significantly shorter deflection. Overall, the predicted responses for all oblique hub impacts were on or above the upper corridor boundaries. The thoracic impact responses remained above the upper corridor boundaries until unloading, while the thoracoabdominal impact responses decreased after the initial peak to instead match the lower boundaries of the corridors. The predicted deflection for the 2.4 m/s lower and middle frontal thoracic bar are within the range of the test results. The predicted lower impact had a higher force level between 20-40 mm, whereas the force level agreed well for the middle impact. For the higher bar impact, the predicted response had a noticeably faster initial force increase with a greater predicted force level and longer deflection, resulting in more energy absorption seen for the SAFER HBM compared to the PMHS responses.



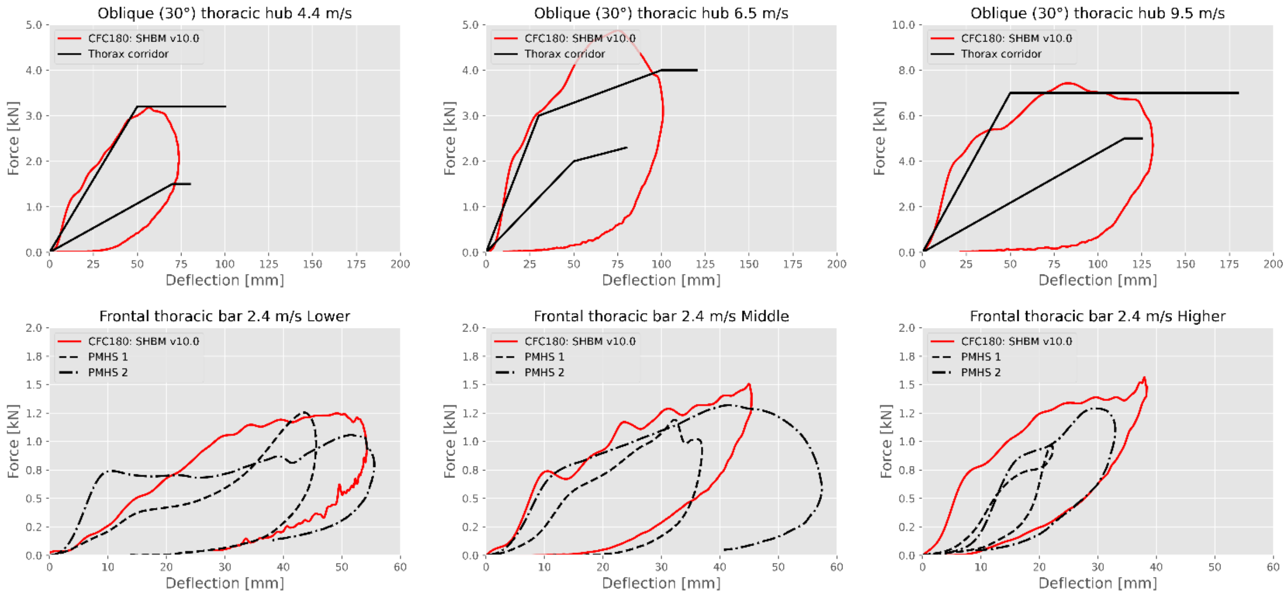


Fig. 2. Force vs. deflection comparison between the experimental test series and the SAFER HBM.

The qualitative results are supported by the quantitative analysis using the overall ISO/TS 18571 ranking. Fig. 3 illustrates the range of ISO/TS 18571 overall ratings describing the amount of correlation between the SAFER HBM response and experimental signals for each test. The range spans from the worst to the best correlation among individual PMHS signals. Additionally, the range includes the ISO/TS 18571 overall rating for the SAFER HBM response compared with the response signal computed from averaging all PMHS signals for each experimental test. For the complete ISO/TS 18571 metrics and the corresponding force vs. time signals for each experimental test, the reader is referred to Appendix D.

The experimental oblique hub tests were conducted on four or more PMHSs and the corresponding range and average response signals indicate a fair (0.58 < rating ≤ 0.80) correlation with the SAFER HBM response for most impact velocities, with the exception of the oblique thoracic 4.4 and 6.5 m/s hub scenario. Mainly in the 6.5 m/s test, the SAFER HBM overpredicted the initial force peak, resulting in a poor correlation grade (Fig. 4a). The predicted frontal thoracoabdominal bar response has a poor correlation grade (rating < 0.58) due to a more rapid initial force increase compared to the PMHS responses (Fig. 4b). However, the predicted response for the thoracic bar impacts, which also only involve two PMHSs per test, have a poor to fair correlation grade with the lower ratings attributed to a higher predicted force level (Fig. 4c).

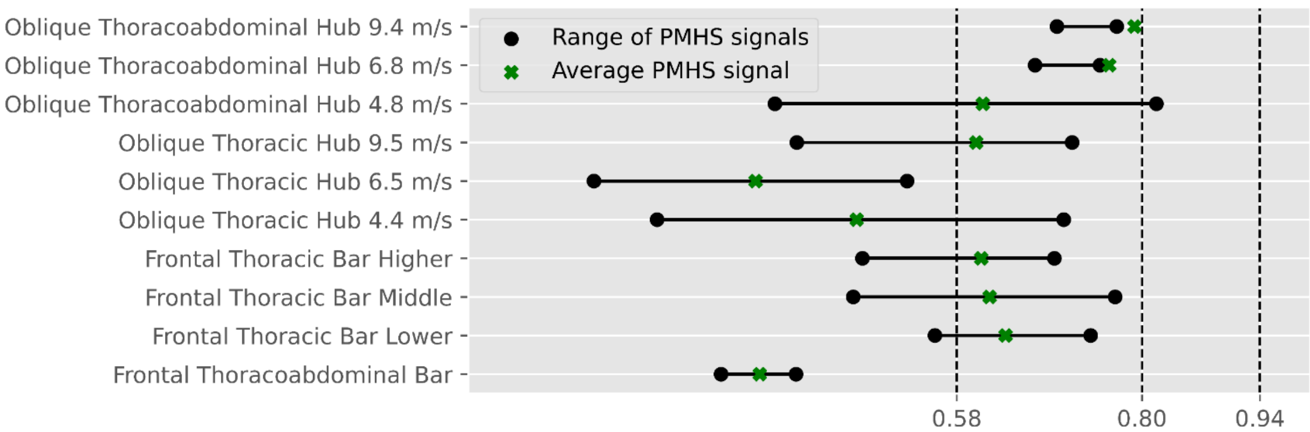
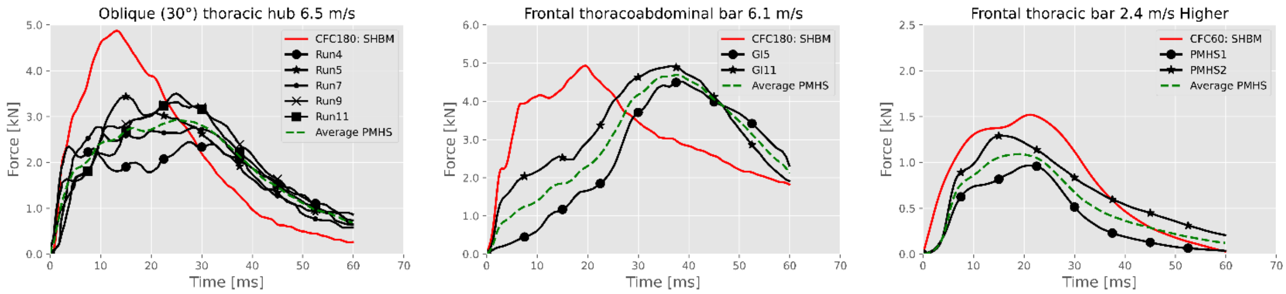


Fig. 3. ISO/TS 18571 overall ratings for force vs. time responses. Ranges span from worst to best correlation among individual PMHS signals with the SAFER HBM response. The rating for the average PMHS signal uses the signal obtained from averaging the individual PMHS signals for each test respectively.



a. b. c.

Fig. 4. Three examples of force vs. time signals used for the quantitative analysis.

Table IV presents a comparison of the predicted average age-adjusted rib fracture risk and the experimental results for cases with two or more fractured ribs (NFR2+) and cases with three or more fractured ribs (NFR3+). The SAFER HBM captured higher risks of rib fracture within a few percentage points, whereas most of the middle to lower risk predictions was within 20 percentage points. The largest deviation was observed for the 9.4 m/s oblique thoracoabdominal hub.

TABLE IV
COMPARISON OF RIB FRACTURE RISK FOR PMHS TESTS AND SAFER HBM

Load configuration		PMHS*			SAFER HBM	
		Average age	NFR 2+ [%]	NFR 3+ [%]	NFR 2+ [%]	NFR 3+ [%]
Thoracoabdominal bar	*6.1 m/s*	69.5	100.0	100.0	99.9	95.8
Oblique thoracoabdominal hub	*4.8 m/s*	55.5	16.7	16.7	0.4	0.0
	6.8 m/s	52.0	75.0	50.0	63.8	16.7
	9.4 m/s	51.0	50.0	50.0	98.7	81.5
Oblique thoracic hub	*4.4 m/s*	49.2	20.0	0.0	4.1	0.2
	6.5 m/s	54.2	100.0	100.0	97.3	83.4
	9.5m/s	43.2	100.0	100.0	100.0	99.5

* The PMHS NFRi+ was computed as: Number of PMHSs with NFRi+/ total number of PMHSs for each test series, i=2,3

IV. DISCUSSION

In this study, a scoping review of the literature identified 1,592 unique records of which 34 satisfied the eligibility criteria. The results have been summarised as a set of impact parameters together describing common thoracic loading experienced by PTW riders in upright PFCS impacts. The scoping review was conducted based on the PRISMA guidelines [39] to ensure transparency and completeness of the evaluated research. Moreover, the literature review did not employ citation chaining by examining the reference lists of the eligible articles to identify additional relevant articles which could potentially have led to relevant studies being missed.

It was found that the in-crash kinematics of PTW riders mainly includes pitch and yaw motion, or a combination thereof, in addition to translational components. The primary loading direction of the thorax was found to range from anterior-posterior to lateral, including also either a superior-inferior or an inferior-superior directed force component. The anterior thoracic region, particularly the middle or superior lateral parts, together with the lateral thoracic regions, are frequent locations in contact with either flat or curved injury sources such as the PTW handlebars or car structures.

To facilitate the selection of relevant load cases for validation of HBMs, the described loading location, distribution, and direction can readily be transformed from rider-to-object impacts into the commonly used object-to-rider validation test setup. Conversely, for novel PMHS tests the force magnitude needs to be transformed into object-to-rider setups specifically for each load condition considering the injury severity, the curvature of the injury source, the effective mass, and the initial impact velocity.

A scoping review of the literature necessitates a clearly defined research question, which poses the challenge of balancing the introduction of sufficient limitations to enable a purposeful review while avoiding an overly narrow analysis of accident scenarios, such that the research no longer constitutes a meaningful contribution in reducing PTW injuries. Therefore, in this study, the research question was restricted to investigating thoracic loading experienced by PTW riders in one of the most common crash configurations (PFCS). To control the scope and complexity of injury mechanisms, certain limitations were introduced. For instance, riders who had fallen prior to impact were excluded to minimise the influence of ground impacts and possible tumbling, which anyway has been shown to decrease with the introduction of antilock braking systems [75]. Cases with pillion riders were also excluded to eliminate the added complexity of interactions with another participant in the crash scenario. This reduced complexity comes at the cost of limiting the applicability of the results to road traffic environments where pillion riders are not commonplace, and thus excludes many accidents in Asia, for example [76]. However, these limitations were necessary because the review aimed to provide information to support validation of HBMs, where clear boundary condition is a necessity.

In addition, there are several limitations with respect to the literature review conducted in this study. While the introduction of the paper discussed the limitation of using ATDs to replicate human responses, it should be noted that these devices are the most used rider substitute in physical testing. However, the design of ATDs, not primarily for PTW applications, may introduce non-biofidelic responses, such as in the pelvis-fuel tank interaction [77]. As such, it is important to acknowledge that the level of biofidelity in ATD kinematics during PTW crashes remains unknown until more full-scale physical testing with PMHSs have been conducted and the results have been compared to results from paired ATD tests. Additionally, only one epidemiological study in the review stratified injuries with respect to multi-vehicle accidents while the most common approach was to present injuries independent of injury source. This means that no robust conclusions could be drawn with respect to the type of thoracic injuries sustained by riders in PFCS accidents.

For the second aim of the paper, the results from the literature review were used to identify four experimental test series based on loading location, direction, distribution, and magnitude, that was used to validate the thorax of the SAFER HBM in terms of kinetics and kinematics, as well as the risk of rib fractures. While the predicted rib fracture risk agreed, it was shown that overall, the SAFER HBM kinetic predictions were in the upper range compared to the PMHSs resulting mainly in fair biofidelity.

The quantitative analysis in terms of ISO/TS 18571 rating was performed both by comparing the SAFER HBM response to the average PMHS signal per load case as well as to each individual PMHS signal to highlight the variability of the PMHS responses. The overall ratings for the average signal are outside the individual PMHS signal ranges for two of the oblique thoracoabdominal hub load cases. The reason was a better match between the SAFER HBM responses with the average signals compared to the individual PMHS signals for these two tests. Since it has been shown that average biomechanical input parameters do not necessarily produce average results [78], it is of interest to also compare the SAFER HBM's response to PMHSs with input parameters deviating from the 50^{th} percentile male in terms of stature, weight, age, and even sex. Thus, in addition to computing the ISO/TS 18571 rating using the average PMHS signal, we recommend that the range of ratings for the individual PMHS signals are also presented.

The ISO/TS 18571 ratings indicate that the predicted oblique thoracoabdominal hub, along with the frontal thoracic bar test series, demonstrate the strongest correlation with the PMHS responses. Conversely, the frontal thoracoabdominal bar impacts show poor correlation grades due to the SAFER HBM prediction deviating from the more gradual PMHS force increase and later occurring peak force. Since only two PMHSs were tested and individual rib cage shape has been shown to vary between individuals [79], it is possible that the force response of the SAFER HBM has high inertial contributions and a rapid force increase because the bar impacts the lower part of the sternum which engages the rib cage and corresponding effective mass. Whereas a different rib cage shape compared to the SAFER HBM could result in the bar striking below the sternum, possibly resulting in less mass engaged and thus a lower inertial contribution to the force response and consequently a more gradual force increase. However, whether the sternum of the PMHSs were struck is unknown since no remarks regarding this were made by the authors [46]. Though, PMHS GI5 were reported to have severe osteoporosis in the ribs hypothesized to explain the low stiffness of that particular PMHS response [46]. Furthermore, compared to the SAEFR HBM, the PMHSs exhibited significantly greater deflection in response to the frontal thoracoabdominal bar impact, exceeding the effective maximum compressive limit of the SAFER HBM. This occurred despite the PMHSs having BMIs of 22.7 and 26.6, indicating an absence of excessive anterior soft tissue forming a paunch that would have supported a larger effective compression distance.

The SAFER HBM predicted an increasing rib fracture risk for increasing number of fractured ribs in the PMHS tests, and even the absolute numbers matched the PMHS results within 20 percentage units. The exception was the 9.4 m/s thoracoabdominal hub impact test where the model predicted a risk close to 100%, while the PMHS tests indicated 50% risk, despite a predicted peak force matching the lower range of PMHS responses. However, comparing the PMHS results from the 9.4 m/s impact to the 6.4 m/s impact from the same test series, the trend was unexpected, with lower PMHS rib fracture risk in 9.4 m/s compared to 6.4 m/s. Normally, a higher energy impact would result in a higher risk of rib fractures, as predicted by the SAFER HBM.

In addition to the SAFER HBM, other HBMs, such as the GHBMC HBM [37] as well as the open-source VIVA+ HBM [80], have been validated for the frontal thoracic and oblique hub impacts chosen in this study [80],[81]. The GHBMC and VIVA+ HBMs have shown good agreement with the experimental data, indicating their potential as alternatives to the SAFER HBM for PFCS applications. Further, the GHBMC and the VIVA+ HBMs have been validated for bar impacts to the abdomen but are to the authors' knowledge yet to be validated for bar impacts engaging the rib cage, which is a limitation of their use in such scenarios.

In the absence of novel PTW-specific tests, validation of HBMs is currently restricted to thoracic PMHS tests developed for occupant loading. Nonetheless, other tests satisfying the identified impact parameters can supplement the four tests selected for validation in this study. For instance, hub-shaped impactors have been examined in [82],[83] for lateral and oblique loading, albeit with lower impact energies than those employed in this study. Similarly, lateral loading to the thorax utilising larger impact surfaces representing contact with the interior side of the door has been investigated in [84-88]. These tests could potentially simulate lower severity impacts to the outside of the door in yaw-dependent impacts.

Upon comparison of the impact parameters used in the four experimental tests with those identified in this study, it is evident that the selected tests represent only a subset of the total parameter space. The anterior midsternal and lateral hub impacts, along with smaller radius frontal bar impacts, do not include blunt impacts to the superior anterior thoracic region, larger cylindrical impactors, or superiorly or inferiorly directed force components, identified as important loading conditions in the literature review. As far as the authors are aware, no study has yet investigated these loading conditions with PMHSs.

The available PMHS test series that load the superior anterior part of the thorax have limited applicability to PTW loading environments since the test setups [89-91] used either quasi-static loading and/or concentrated point loads engaging less than three ribs on one side. Although the available PMHS tests are useful for validating parts of the thoracic model, there is a need for new experimental test series using complete PMHS thoraxes that incorporate blunt impacts to the superior anterior thoracic region, larger cylindrical impactors, or superiorly or inferiorly directed force components. For this purpose, novel PMHS tests should employ impactors with different sizes and radii ranging from 5-25 cm. Additionally, new test setups should strive to incorporate the influence of force components in the superior-inferior or the inverse direction, possibly by allowing pendulum-based impacts to strike reclined or forward leaning PMHSs.

Finally, this study represents a significant contribution to the existing body of literature on PTW rider thoracic loading, as it is the first of its kind to review available knowledge on this topic in a transparent and reproducible manner. By focusing specifically on PFCS impacts, which is one of the most common crash configurations involving PTWs, the study provides a basis for understanding the necessary thoracic loading conditions for PTW riders.

While this study represents an important step forward in providing an enhanced understanding of the injurious loading to PTW riders, it is important to note that there is still a lot of work remaining. Future studies are needed to investigate other common PTW accident scenarios and injury mechanisms in order to fully understand the necessary loading conditions for supporting HBM validation and development of robust countermeasures. Ultimately, the goal of this research is to reduce the incidence of high-severity injuries in PTW accidents, and continued efforts in this area are crucial for achieving this objective. This knowledge is essential for prioritising the validation of HBMs and ultimately to enable the development of effective thoracic injury countermeasures for PTW riders to reduce the risk of high-severity injuries.

V. CONCLUSIONS

In conclusion, this study provides a condensed set of four impact parameters that define the general thoracic loading experienced by PTW riders in upright PTW frontal impacts to the side of passenger cars. These parameters, which include location, distribution, direction, and magnitude, are primarily focused on the anterior to lateral thoracic regions over the entire height of the thorax, with the main loading direction ranging from anterior-posterior to lateral, with either superior-inferior or inferior-superior directed force components. The study also highlights the need for novel PMHS tests to aid future HBM validation, as current validation load cases have not loaded the thorax above the 4th intercostal space and do not include vertical force components.

Furthermore, four thoracic, whole-body level PMHS tests matching the identified impact parameters were selected for the validation of the SAFER HBM. The model demonstrated fair to good biofidelity for frontal hub and oblique hub impacts, and poor to fair biofidelity due to a stiffer response compared to the experimental bar impacts. This study demonstrates the usefulness of the identified impact parameters to support PTW specific validations for HBMs to accurately represent thoracic loading in upright PTW frontal impacts to the side of passenger cars.

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VIII. Appendix

A. Scoping Review - Electronic Search Strategy

Search strategy for Scopus, Web of Science, PubMed, and Google Scholar. No review protocol was reported beforehand.

Scopus

(TITLE-ABS-KEY (motorcycl* OR ptw OR "powered two wheeler") AND TITLE-ABS-KEY (car OR vehicle OR motor-vehicle) AND TITLE-ABS-KEY (cras* OR acciden* OR impac* OR injur* OR trauma) AND TITLE-ABS-KEY (body OR rider OR thorax OR thoracic OR chest OR trunk OR torso OR rib)) AND (LIMIT-TO (LANGUAGE , "English"))

Web of Science

(((TS=(motorcycl* OR ptw OR "powered two wheeler" OR "powered two-wheeler" OR "powered two wheelers" OR "powered two-wheelers")) AND TS=(car OR vehicle OR motor-vehicle)) AND TS=(cras* OR acciden* OR impac* OR injur* OR trauma)) AND TS=(body OR rider OR thorax OR thoracic OR chest OR trunk OR torso OR rib)

PubMed

("motorcycl*"[Title/Abstract] OR "ptw"[Title/Abstract] OR "powered two wheeler"[Title/Abstract] OR "powered two-wheeler"[Title/Abstract] OR "powered two wheelers"[Title/Abstract] OR "powered two-wheelers"[Title/Abstract]) AND ("car"[Title/Abstract] OR "vehicle"[Title/Abstract] OR "motor-vehicle"[Title/Abstract]) AND ("cras*"[Title/Abstract] OR "acciden*"[Title/Abstract] OR "impac*"[Title/Abstract] OR "injur*"[Title/Abstract] OR "traum"[Title/Abstract]) AND ("body"[Title/Abstract] OR "rider"[Title/Abstract] OR "thorax"[Title/Abstract] OR "thoracic"[Title/Abstract] OR "chest"[Title/Abstract] OR "trunk"[Title/Abstract] OR "torso"[Title/Abstract] OR "rib"[Title/Abstract])

Google Scholar

Motorcycle|motorcyclist|motorcyclists|ptw|"powered two wheeler"|"powered two-wheeler"
Car|cars|vehicle|vehicles|"motor-vehicle"
crash|crashes|accident|accidents|impact|impacts|injury|injuries|trauma
body|rider|thorax|thoracic|chest|trunk|torso|rib

B. Scoping Review - Characteristics of Sources of Evidence

TABLE B.I
CHARACTERISTICS OF REFERENCES AND DATA EXTRACTED FOR SCOPING REVIEW

Reference	*Article type*	*Data origin*	*Extracted data [category]*
[12]	Epidemiological Accidentological	Accident data base	Injury sources
[13]	Epidemiological Accidentological Experimental Numerical	Accident data base Physical PMHS crash test Multibody simulations	In-crash kinematics Loading direction Injury source Loading magnitude
[17]	Epidemiological Accidentological	Accident data base	In-crash kinematics Injury source Loading magnitude
[18]	Epidemiological Accidentological Numerical	Hospital emergency records Multibody simulations	In-crash kinematics Loading direction Injury source Loading location
[19]	Epidemiological Accidentological	Accident data base	Injury sources
[22]	Numerical study	FE human body model simulations	Injury source Loading magnitude
[24]	Numerical	Physical ATD crash test FE ATD simulations	In-crash kinematics Loading direction Injury source
[26]	Experimental	Physical ATD crash test	In-crash kinematics Injury source
[27]	Experimental Numerical	Physical ATD crash test FE simulations	In-crash kinematics Loading direction Injury source
[36]	Numerical	FE human body model simulations	Injury source
[40]	Numerical study	Multibody simulations	Loading location Loading magnitude
[41]	Numerical	Hybrid multibody and FE human body model simulations	In-crash kinematics Loading direction
[42]	Epidemiological	Accident data base	Loading location
[53]	Review	Physical ATD crash tests	In-crash kinematics
[54]	Experimental	Physical ATD crash test	In-crash kinematics Loading direction Injury source
[55]	Numerical	Physical ATD crash test Multibody simulations	In-crash kinematics Loading direction Injury source
[56]	Experimental	Physical ATD crash test	In-crash kinematics Loading direction
[57]	Experimental	Physical ATD crash test	In-crash kinematics Injury source Loading magnitude
[58]	Experimental	Physical ATD crash test	In-crash kinematics

			Injury source
[59]	Experimental	Physical ATD crash test	In-crash kinematics Injury source
[60]	Experimental	Physical PMHS crash test Multibody simulations	In-crash kinematics
[61]	Review	Accident investigation data Physical ATD crash test	In-crash kinematics Loading direction
[62]	Epidemiological Accidentological Numerical	Accident data base Multibody simulations	In-crash kinematics Loading direction Injury source
[63]	Epidemiological Accidentological Numerical	Accident data base Multibody simulations FE simulations	Loading direction Injury source Loading magnitude
[64]	Numerical	Multibody simulations	In-crash kinematics Loading direction Injury source Loading magnitude
[65]	Epidemiological Accidentological	Accident data base	In-crash kinematics Injury source
[66]	Review	Accident data base Physical ATD crash test	In-crash kinematics Injury source
[67]	Epidemiological Accidentological	Accident data base	In-crash kinematics Injury source
[68]	Numerical	Multibody simulations	In-crash kinematics Injury source
[70]	Epidemiological Accidentological	Accident data base	In-crash kinematics Injury source
[71]	Numerical	Dynamic mathematical single mass model	In-crash kinematics Injury source
[72]	Epidemiological Accidentological	Accident data base	In-crash kinematics Loading direction Injury source
[73]	Epidemiological Accidentological	Accident data base	Injury sources
[74]	Epidemiological Accidentological	Accident data base	Injury sources

C. Scoping Review - Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) Checklist

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	Not done
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	Not possible within the 200 word limit for abstract
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	1-2
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	1-3 Aim, Table I and data extraction in method
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	15
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	2-3
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	2-3
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	16
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	2-3
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	3
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	3
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	Not done
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	3
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	2
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	17-18
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	Not done
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	17-18

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	5-7
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	6-7
Limitations	20	Discuss the limitations of the scoping review process.	9-11
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	11
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	11-12

JBI = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews.

* Where *sources of evidence* (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.

† A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with *information sources* (see first footnote).

‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting.

§ The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

D. ISO/TS 18571 Rating

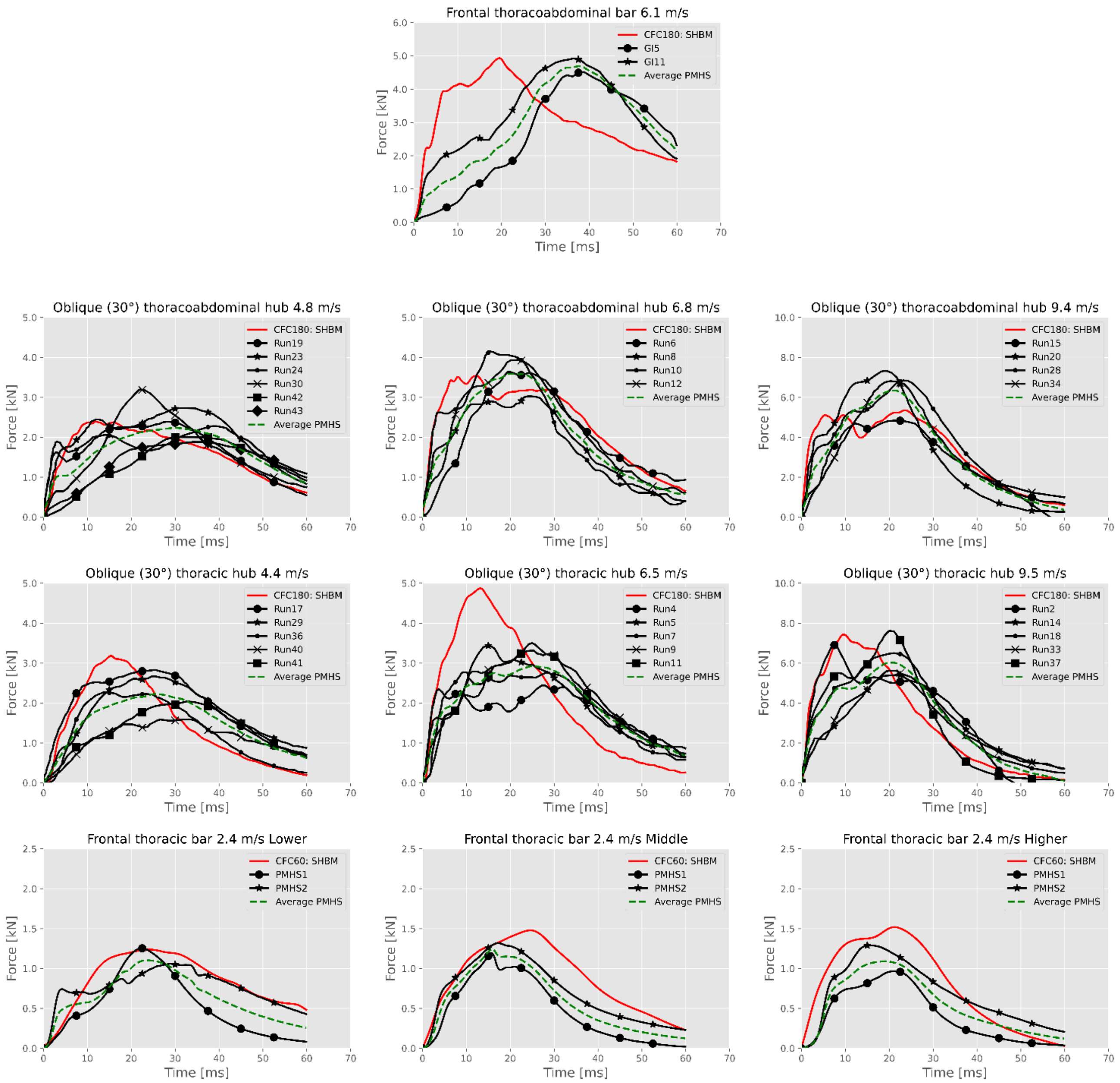

Fig. D.1. Force vs. time signals used for ISO/TS 18571 rating.

TABLE D.I

THE COMPLETE ISO/TS 18571 METRICS FOR THE ANALYSED FORCE VS. TIME SIGNALS FOR THREE EXPERIMENTAL SERIES

Test signal	PMHS code	Age	BMI	Sex	Corridor	Phase	Magnitude	Slope	Overall
Frontal Thoracoabdominal Bar	GI5	65	22,7	F	0.216	0.000	0.728	0.341	0.300
Frontal Thoracoabdominal Bar	GI11	74	26,6	M	0.351	0.000	0.907	0.336	0.389
Frontal Thoracoabdominal Bar	Averaged	-	-	-	0.266	0.000	0.860	0.337	0.346
Frontal Thoracic Bar Lower	PMHS1	88	30,1	M	0.386	0.758	0.576	0.663	0.554
Frontal Thoracic Bar Lower	PMHS2	65	28,8	M	0.673	1.000	0.872	0.477	0.739

Frontal Thoracic Bar Lower	Averaged	-	-	-	0.453	0.850	0.781	0.653	0.638
Frontal Thoracic Bar Middle	PMHS1	88	30,1	M	0.234	0.767	0.344	0.705	0.457
Frontal Thoracic Bar Middle	PMHS2	65	28,8	M	0.689	0.825	0.921	0.718	0.768
Frontal Thoracic Bar Middle	Averaged	-	-	-	0.443	0.792	0.695	0.720	0.619
Frontal Thoracic Bar Higher	PMHS1	88	30,1	M	0.270	0.967	0.248	0.586	0.468
Frontal Thoracic Bar Higher	PMHS2	65	28,8	M	0.584	0.850	0.840	0.622	0.696
Frontal Thoracic Bar Higher	Averaged	-	-	-	0.436	0.908	0.659	0.603	0.609
Oblique thoracic hub 4.4 m/s	Run17	29	23,5	M	0.481	0.833	0.780	0.472	0.610
Oblique thoracic hub 4.4 m/s	Run29	52	21,5	F	0.319	0.483	0.804	0.482	0.482
Oblique thoracic hub 4.4 m/s	Run36	37	19,4	M	0.659	0.825	0.809	0.582	0.707
Oblique thoracic hub 4.4 m/s	Run40	64	23,8	M	0.229	0.300	0.359	0.000	0.224
Oblique thoracic hub 4.4 m/s	Run41	64	23,8	M	0.206	0.000	0.659	0.115	0.237
Oblique thoracic hub 4.4 m/s	Averaged	-	-	-	0.327	0.583	0.745	0.323	0.461
Oblique thoracic hub 6.5 m/s	Run4	63	23,1	M	0.246	0.000	0.255	0.000	0.149
Oblique thoracic hub 6.5 m/s	Run5	38	20,3	M	0.459	0.650	0.714	0.324	0.521
Oblique thoracic hub 6.5 m/s	Run7	66	22,2	M	0.347	0.825	0.541	0.313	0.474
Oblique thoracic hub 6.5 m/s	Run9	64	21,1	M	0.299	0.392	0.740	0.256	0.397
Oblique thoracic hub 6.5 m/s	Run11	40	24,9	F	0.350	0.158	0.755	0.291	0.381
Oblique thoracic hub 6.5 m/s	Averaged	-	-	-	0.318	0.467	0.602	0.000	0.341
Oblique thoracic hub 9.5 m/s	Run2	49	34,5	M	0.618	0.025	0.448	0.242	0.390
Oblique thoracic hub 9.5 m/s	Run14	49	23,6	M	0.382	0.275	0.785	0.404	0.446
Oblique thoracic hub 9.5 m/s	Run18	29	23,5	M	0.595	0.550	0.918	0.512	0.634
Oblique thoracic hub 9.5 m/s	Run33	52	21,5	F	0.465	0.458	0.801	0.419	0.522
Oblique thoracic hub 9.5 m/s	Run37	37	19,4	M	0.755	0.683	0.909	0.482	0.717
Oblique thoracic hub 9.5 m/s	Averaged	-	-	-	0.586	0.542	0.865	0.438	0.603
Oblique thoracoabdominal 4.8 m/s	Run19	29	23,5	M	0.788	1.000	0.934	0.575	0.817
Oblique thoracoabdominal 4.8 m/s	Run23	62	26,9	M	0.621	0.917	0.795	0.631	0.717
Oblique thoracoabdominal 4.8 m/s	Run24	62	26,9	M	0.493	1.000	0.769	0.531	0.657

Oblique thoracoabdominal 4.8 m/s	Run30	52	21,5	F	0.673	0.483	0.855	0.609	0.659
Oblique thoracoabdominal 4.8 m/s	Run42	64	23,8	M	0.367	0.000	0.843	0.243	0.364
Oblique thoracoabdominal 4.8 m/s	Run43	64	23,8	M	0.394	0.042	0.797	0.288	0.383
Oblique thoracoabdominal 4.8 m/s	Averaged	-	-	-	0.580	0.492	0.924	0.478	0.611
Oblique thoracoabdominal 6.8 m/s	Run6	38	20,3	M	0.741	0.550	0.918	0.416	0.673
Oblique thoracoabdominal 6.8 m/s	Run8	66	22,2	M	0.553	1.000	0.855	0.576	0.707
Oblique thoracoabdominal 6.8 m/s	Run10	64	21,1	M	0.628	0.950	0.828	0.586	0.724
Oblique thoracoabdominal 6.8 m/s	Run12	40	24,9	F	0.770	0.792	0.913	0.505	0.750
Oblique thoracoabdominal 6.8 m/s	Averaged	-	-	-	0.694	0.925	0.939	0.553	0.761
Oblique thoracoabdominal 9.4 m/s	Run15	49	23,6	M	0.781	0.758	0.938	0.468	0.745
Oblique thoracoabdominal 9.4 m/s	Run20	29	23,5	M	0.631	0.975	0.724	0.605	0.713
Oblique thoracoabdominal 9.4 m/s	Run28	62	26,9	M	0.738	0.892	0.823	0.657	0.770
Oblique thoracoabdominal 9.4 m/s	Run34	64	16,2	M	0.718	0.767	0.845	0.447	0.699
Oblique thoracoabdominal 9.4 m/s	Averaged	-	-	-	0.780	0.917	0.879	0.598	0.791