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Scoping Review on Validation Data for Submarining Prediction in Automotive Crashes

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1. Introduction

Submarining, defined as *"the lap belt slides over iliac crest with lap belt forces effecting the internal abdominal organs during forward displacement of the lower torso"* (Adomeit & Heger, 1975), can lead to injuries related to belt-to-abdominal loading in frontal automotive crashes. Injuries to the abdominal organs are therefore often used as a proxy for the submarining event, when studying the epidemiology of submarining scenarios from real-world data (Couturier et al., 2007; Poplin et al., 2015). Injuries to the abdominal organs can, however, stem from multiple sources, not strictly related to the submarining outcome (Poplin et al., 2015). As a result, retrospective studies of submarining in real-world crashes are difficult and a prospective approach using models is considered an important complement.

Prospective models can be both physical, i.e. Anthropometric Testing Devices (ATDs), or virtual, i.e. finite element ATDs (FE-ATDs) or FE human body models (FE-HBMs). The validity of such models, i.e. the confidence in their predicted response, requires data from post-mortem human subject (PMHS) tests targeting the submarining phenomena, including both submarining and non-submarining scenarios. Tests that result in only one or the other can also be important, however, they only facilitate validation of main trends and do not identify the actual thresholds for submarining. Unfortunately, few studies providing PMHS data in submarining scenarios exist, and a review on this topic has not been presented in the literature. To identify gaps in the available data and aid future research, a scoping review would present a structured method to summarize the body of knowledge concerning validation data for submarining scenarios (Tricco et al., 2018).

The aim of this report was, hence, to perform a scoping review of the literature to identify all available PMHS tests on submarining.

2. Method

With the aim of identifying all publications on PMHS data in submarining scenarios, a scoping review of the literature was conducted based on the PRISMA Extension for Scoping Reviews (PRISMA-ScR) (Tricco et al., 2018). Methods of the analysis with inclusion and exclusion criteria were specified in advance and documented in a protocol, see **Tab. 1**.

Tab. 1 Scoping review protocol

Objectives

To identify PMHS based validation data for submarining scenarios to be used in ATD or HBM development.

Eligibility Criteria

Types of studies: Any study on PMHS's in submarining scenarios, or scenarios where the lap belt could slide from the hip to the abdomen in a submarining like motion. English language restriction was applied, however, no publication date or publication status restrictions were imposed.

Types of participants: PMHS without sex, age, or anthropometric restrictions.

Types of interventions: Loading scenarios where the belt slides from the hip to the abdomen, either from stationary setups with a fixated PMHS or from dynamic setups using e.g., a sled test.

Types of outcome measures: Submarining outcome, timing, kinematic response.

Information Sources

- SCOPUS
- Web of Science
- PubMed

Search

The following search term was used: "submarining"

Study Selection

Go through the steps of: Identification, duplicate removal, abstract screening, and full-text article eligibility using the inclusion/exclusion criteria. From the resulting list of papers, references and citing articles will be considered for additional records not found by the search.

Inclusion criteria

- PMHS sled test with focus on submarining
- PMHS frontal sled test where submarining results were reported even though this wasn't the primary objective of the study
- Stationary PMHS test where loading was created to replicate a submarining scenario

Exclusion criteria

- Any test only testing Anthropomorphic Test Devices (ATDs)
- Simulation based studies
- Submarining was only discussed, not evaluated in the reported tests

All scientific publications using PMHSs to study the submarining scenario were considered, except restricting for English, no other restrictions were imposed on PMHS characteristics, publication date or publication status. The review was limited to studies focusing on the submarining scenario, i.e., studies addressing validation of related topics, such as abdominal response post-submarining, knee-thigh-hip response, fat/muscle material models and assigned properties, etc., were not included in the review. While such studies are still relevant for simulating and predicting a submarining response, they are unsuitable for validating the submarining scenario explicitly. Studies were identified by searching the term "submarining" in electronic databases and scanning reference lists of articles identified by this search. No study was excluded based on its estimated validity or significance for validation purposes. The search was applied to Scopus, Web of Science, and PubMed on 10 May 2023.

The identification of records was performed sequentially as presented in **Fig. 1**. The initial list of records was first filtered for duplicates followed by an abstract screening step. Potential records of interest were checked in a full-text eligibility step in which inclusion in the final sample required records to satisfy at least one inclusion criteria and none of the exclusion criteria. The review was performed by the main author of this report, however, records in which fulfillment of inclusion and/or exclusion criteria were ambiguous, the report reviewers were consulted for a joint decision.

Data extraction included PMHS characteristics (sex, age, stature, and weight), type of loading scenario (stationary or moving sled), occupant posture (standard driving, upright, or reclined), and submarining outcome. The data were analyzed through simple descriptive statistics and general summaries. No attempt was made to contact the original researchers for records with missing data, primarily because this issue related to studies carried out in the 1970s and 1980s. Care was taken not to count the same PMHS multiple times if included in more than one record.

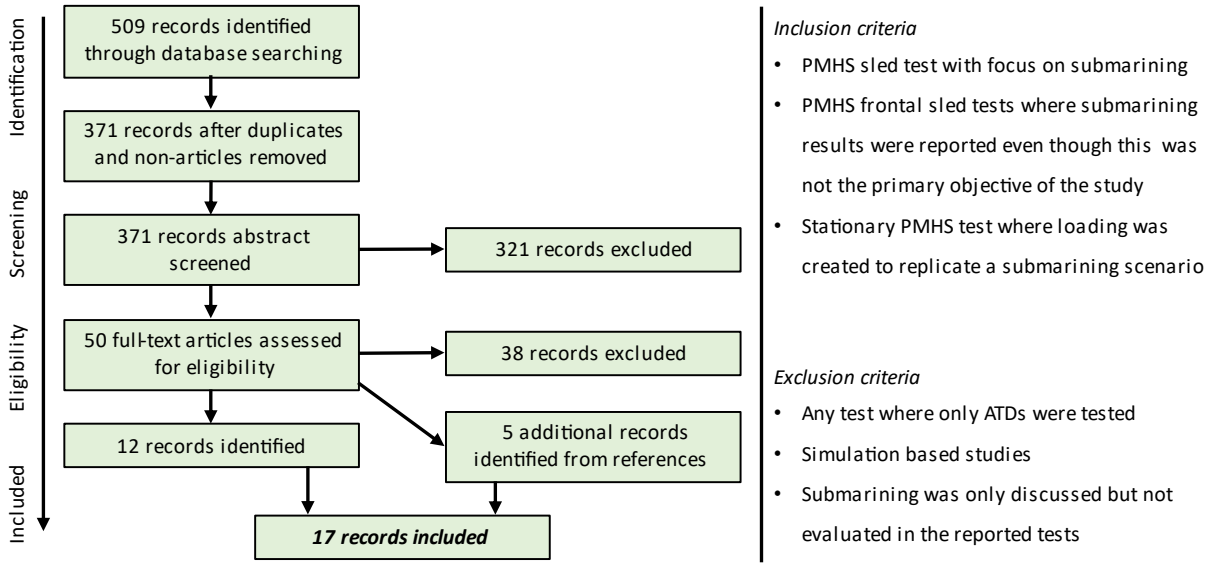

Fig. 1 Flow of information through the different phases of the scoping review, together with the inclusion and exclusion criteria

3. Results

The scoping review resulted in 509 identified records, of which 371 were kept for abstract screening, 50 were considered in the full-text eligibility check, and 12 were identified to fulfill the inclusion and exclusion criteria. In addition, five more records were identified from the references of the search results for a total of 17 included records, see **Fig. 1** for an overview and **Tab. 2** for a complete list of included records.

Tab. 2 List of included records from scoping review

Authors	Title	Year	Source
Patrick L.M., Levine R.S.,	*Injury to unembalmed belted cadavers in simulated collisions.*	1975	Stapp Car Crash Conference Proceedings
Levine R.S., Patrick L.M., Begeman P.C., King A.I.	*Effect of quadriceps function on submarining*	1978	American Association for Automotive Medicine 22nd Conference
Leung Y.C., Tarrière C., Fayon A., Mairesse P., Delmas A., Banzet P.,	*A comparison between part 572 dummy and human subject in the problem of submarining*	1979	SAE Technical Papers
Leung Y.C., Tarrière C., Fayon A., Mairesse P., Banzet P.,	*An anti-submarining scale determined from theoretical and experimental studies using three-dimensional geometrical definition of the lap-belt*	1981	SAE Technical Papers
Kallieris D., Mellander H., Schmidt G., Barz J., Mattern R.,	*Comparison between frontal impact tests with cadavers and dummies in a simulated true car restrained environment*	1982	SAE Technical Papers
Uriot J., Baudrit P., Potier P., Trosseille X., Petit P., Guillemot H., Guérin L., Vallancien G.,	*Investigations on the belt-to-pelvis interaction in case of submarining.*	2006	Stapp Car Crash Journal
Michaelson J., Forman J., Kent R., Kuppa S.,	*Rear seat occupant safety: Kinematics and injury of PMHS restrained by a standard 3-point belt in frontal crashes.*	2008	Stapp Car Crash Conference Proceedings
Forman J., Lopez-Valdes F., Lessley D., Kindig M., Kent R.,	*Rear seat occupant safety: an investigation of a progressive force-limiting, pretensioning 3-point belt system using adult PMHS in frontal sled tests.*	2009	Stapp Car Crash Conference
Forman J., Lopez-Valdes F.J., Lessley D., Kindig M., Kent R., Bostrom O.,	*The effect of obesity on the restraint of automobile occupants*	2009	AAAM Conference
Luet C., Trosseille X., Drazétic P., Potier P., Vallancien G.,	*Kinematics and dynamics of the pelvis in the process of submarining using PMHS sled tests.*	2012	Stapp Car Crash Journal
Uriot J., Potier P., Baudrit P., Trosseille X., Petit P., Richard O., Compigne S., Masuda M., Douard R.,	*Reference PMHS sled tests to assess submarining*	2015	Stapp Car Crash Journal
Uriot J., Potier P., Baudrit P., Trosseille X., Richard O., Douard R.,	*Comparison of HII, HIII and THOR dummy responses with respect to PMHS sled tests*	2015	IRCOBI Conference
Kim T., Park G., Montesinos S., Subit D., Bolton J., Overby B., Forman J., Crandall J., Kim H.	*Abdominal characterization under lap belt loading.*	2015	ESV Conference
Shaw G., Lessley D., Ash J., Acosta S., Heltzel S., Riley P., Kim T., Crandall J.,	*Pelvic restraint cushion sled test evaluation of pelvic forward motion*	2018	Traffic Injury Prevention
Trosseille X., Petit P., Uriot J., Potier P., Baudrit P., Richard O., Compigne S., Masuda M., Douard R.,	*Reference PMHS sled tests to assess submarining of the small female*	2018	Stapp Car Crash Journal
Richardson R., Donlon J.-P., Jayathirtha M., Forman J.L., Shaw G., Gepner B., Kerrigan J.R., Östling M., Mroz K., Pipkorn B.,	*Kinematic and injury response of reclined PMHS in frontal impacts*	2020	Stapp Car Crash Journal

In the included records, a total of 145 PMHSs (68 males, 23 females, 54 unknown) were subjected to a total of 171 loadings. Of these PMHSs, 64 were recorded showing a submarining response in at least one loading scenario. The average male PMHS was 63.8 years old (SD: 19.1 years), had an average stature of 1.75 m (SD: 0.07 m), an average weight of 73.1 kg (SD: 16.6 kg), and an average of BMI 23.8 kg/m^2 (SD: 4.7 kg/m^2), while the average female PMHS was 64.8 years old (SD: 15.8 years), had an average stature of 1.60 m (SD: 0.09 m), an average weight of 56.9 kg (SD: 16.5 kg), and an average of BMI 22.0 kg/m^2 (SD: 5.1 kg/m^2). **Fig. 2** shows a scatter plot of stature vs. weight aggregated by sex, for all subjects for whom this data was reported. A cluster of data points were found around the average male (approx. 1.75 m and 77 kg), while fewer data points were found around the average female (approx. 1.62 m and 62 kg). Instead, the female data are primarily focused on a small female and in a smaller cluster around a stature of 1.7 m. A total of 7 obese (BMI > 30 kg/m^2) and 3 large males (>1.88 m) PMHSs were identified.

Of the included records, three used stationary PMHSs (Kim et al., 2015; Moreau et al., 2021; Uriot et al., 2006), two studied a reclined posture (Moreau et al., 2021; Richardson et al., 2020), one studied an upright (90° between seat and backrest) posture (Uriot et al., 2006), while the remainder used a sled test with a standard driving posture. In the reclined postures, only two cases of submarining, one being a partial submarining on one side, were identified. All records were confirmed to use unembalmed PMHs, except two who were unspecified (Leung et al., 1979; Levine et al., 1978).

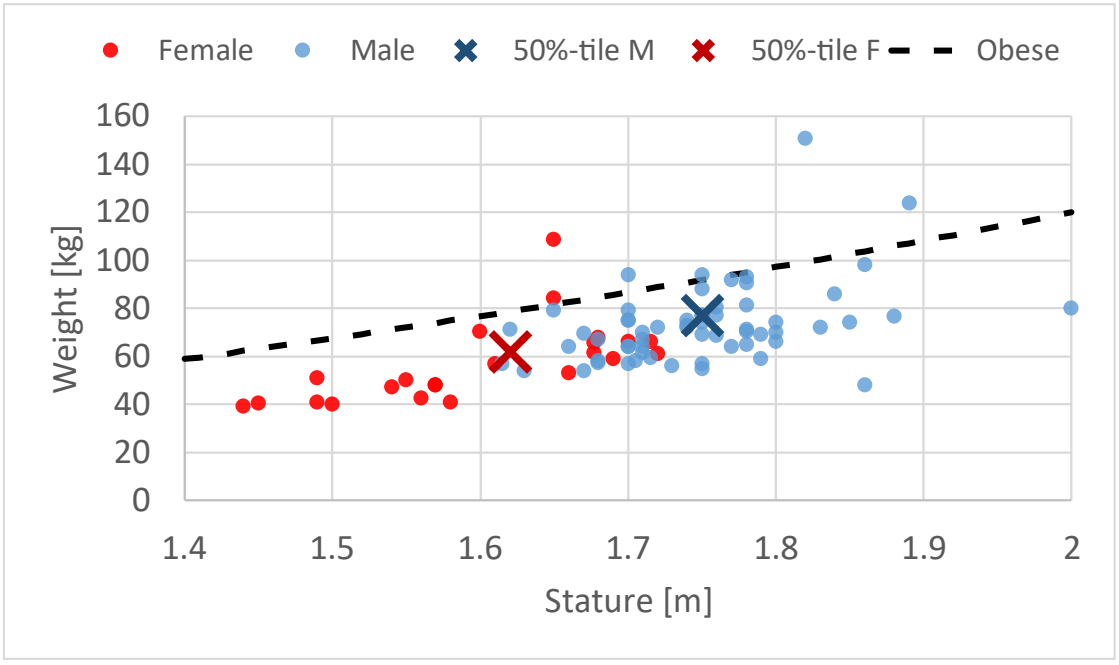

Fig. 2 Stature vs. weight for PMHSs in included records (when data were reported). The 50%ile male and female are marked with a blue/red cross and obesity (BMI = 30 kg/m^2) with a dashed black line

4. Discussion

The scoping review resulted in 17 identified records totaling 145 PMHSs in 171 loadings. While this could be considered a good sample for validation, there are some limitations associated with using this data. For example, the records prior to the 2000s (Kallieris et al., 1982; Leung et al., 1979, 1981; Levine et al., 1978; Patrick & Levine, 1975), include limited data on both loading scenario and kinematic response, which makes validation challenging or even impossible. Hence, seven of the identified records, totaling 83 PMHSs, are not suitable for validation purposes. Furthermore, several of the records require validated models of seat and belt systems (Forman, Lopez-Valdes, Lessley, Kindig, Kent, & Bostrom, 2009; Forman, Lopez-Valdes, Lessley, Kindig, Kent, Ridella, et al., 2009; Michaelson et al., 2008; Moreau et al., 2021; Richardson et al., 2020; Shaw et al., 2018), which are difficult to reverse engineer without access to the physical object and extensive knowledge about its design. Such models are often not publicly available, or available at all, which make the data difficult to use for validation purposes, unless the authors behind a study have access to and are willing to share such information. In addition, each record is typically focused on a small subpopulation, most often the 50%ile male or a 5%ile female, in normal driving postures. This means that validation data for submarining outcomes are lacking or very limited for the 50%ile female, obese subjects, large males/females, or reclined subjects. For reclined occupants specifically, only one case of submarining in a stationary PMHS setup (Moreau et al., 2021), and a partial submarining (one side) for one of five PMHSs in a sled setup (Richardson et al., 2020), has been recorded. Given these limited cases, and that the majority PMHS response in each setup is no-submarining, model validation for submarining outcome in reclined scenarios is currently not viable.

A challenge with the identified records is the resulting skeletal fractures and their unknown effect on PMHS kinematics and the submarining outcome. These include both substantial ribcage fractures (Forman, Lopez-Valdes, Lessley, Kindig, Kent, Ridella, et al., 2009; Luet et al., 2012; Shaw et al., 2018; Trosseille et al., 2018; Uriot et al., 2015) and pelvis fractures (Luet et al., 2012; Moreau et al., 2021; Richardson et al., 2020; Shaw et al., 2018; Trosseille et al., 2018; Uriot et al., 2006, 2015). A favorable kinematic outcome to avoid submarining is to restrain the hip while letting the torso pivot forward (Adomeit & Heger, 1975). A “flailed chest” could, hence, cause greater forward movement of the torso which could potentially reduce the risk of submarining. Similarly, since the lap belt load is applied to the pelvis, it is likely that a pelvic fracture could have induced a submarining outcome, although the records include examples of PMHSs with pelvic fracture who both did submarine and who did not submarine, so the outcome is not given. While fracture mechanics can be included in HBM simulations, fracture is a very chaotic and subject specific event which all HBMs are not aimed at capturing. The motivation is that developers of vehicle safety systems do not target events post-fracture, since the system has failed at this stage, instead, these models focus on predicting the risk of fracture, using tools such as an injury risk function (IRF). However, their kinematic response post-fracture can, therefore, be questionable. This issue is further accentuated for the ATD models who, by design, are built not to break. Excluding PMHSs that have sustained fractures post-injury when validating these non-fracturing models, as suggested by certain authors (Trosseille et al., 2018; Uriot et al., 2006), would greatly limit the available validation data for submarining outcomes.

Another challenge is the varying definitions used to identify if submarining occurred in the recorded experiments or not. Several signals have been suggested, such as lap belt force drop, belt-to-pelvis angle, pelvis rotation, knee forward displacement, hip-to-torso relative kinematics, abdominal injury pattern, pelvic strain, video analysis, etc. However, using a single measurement signal can sometimes be misleading and could result in inaccurate classification of submarining, which would harm future model validation efforts. Instead, the most robust evaluation of submarining occurs when multiple signals are combined (Guettler et al., 2023; Rouhana et al., 1989; Trosseille et al., 2018), but even then, the resulting measurements might lack a resounding submarining signal and its occurrence could be questioned (Uriot et al., 2015).

A literature review is never more than a snapshot in time, and submarining, especially in reclined scenarios, is an active research topic at many institutes. These ongoing efforts complement some of the gaps identified in the current review and the identified list of records would not be complete without mentioning them. The following bullet points summarize current projects known to the author. To enable easier traceability, the bullet points include paper references to pre-studies for the experiments, and in some cases actual validation data if they were published/indexed after the current literature search was conducted (10 May 2023). Studies aiming to validate prospective models for submarining scenarios should consider this list for additional data.

- University of Michigan Transportation Research Institute (UMTRI) are running tests under the National Highway Transportation Safety Administration (NHTSA) funded project, Automated Vehicle Occupant Kinematics (AVOK). The experiments target a 50%ile male subject in upright and reclined seated postures using a semi-rigid seat (Boyle et al., 2019).
- Medical College of Wisconsin are running tests under the NHTSA funded project AVOK. The experiments target a 5%ile female subject and an obese subject in upright and reclined seated postures using a semi-rigid seat (Somasundaram et al., 2022, 2023).
- University of Virginia (UVA) are expanding their reclined 50%ile male semi-rigid seat experiments with 50%ile female subjects (Shin et al., 2023), and their stationary reclined experiments with above-normal BMI subjects (Richardson et al., 2023).
- Comillas Pontifical University are running tests under the consortium Enable New Occupant Seating Positions (ENOP), which is coordinated by Laboratory of Accidentology, Biomechanics and Human Behavior (LAB). The experiments target a 50%ile male subject in upright to reclined postures using a semi-rigid seat (Östling et al., 2022).
- Virginia Polytechnic Institute and State University are running tests under the NHTSA funded project “Rear-Seat Frontal Crash Protection Research with Application to Vehicles with Automated Driving Systems”. The experiments target a 50%ile male subject in varying real rear seat vehicle interiors (Guettler et al., 2023).
- Centre Européen d’Etudes de Sécurité et d’Analyse des Risques (CEESAR) are expanding their semi-rigid seat experiments with 50%ile male subjects in reclined postures (Baudrit et al., 2022).

5. Conclusion

This report has summarized the available PMHS validation data on submarining and identified 17 records. The list is estimated to include a sufficient validation set for the 50%ile male and for a small female in upright driving postures, however, it currently lacks data for the 50%ile female, obese subjects, large females/males, and reclined subjects. Fortunately, the complementary list presented in the Discussion, regarding current research at several institutes, will likely fill some of these gaps, as long as both submarining and non-submarining outcomes are targeted. Future models should, hence, have access to a broad set of data to validate both baseline models and population representative versions, given that the data become publicly available. Reaching consensus within the research community on what defines submarining, and how to identify its occurrence in PMHS experiments, would significantly improve the collective effort and make the validation of future models both more robust and less prone to subjective assessments.

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