Comparison of kinematic response between MADYMO Human Body Model and PMHS in reclined posture

Rui Dai, Wenxuan Shen, Puyuan Tan, Jisi Tang, Qing Zhou*

Abstract This study investigates the kinematic responses of occupants in a reclined posture during frontal collisions, using the MADYMO Human Body Model (HBM) and comparing it with post-mortem human subjects (PMHS) data. Previous research indicates that fully reclined seats significantly increase the risk of injury and mortality in traffic accidents. A series of simulations were conducted in a MADYMO environment, replicating the conditions of PMHS experiments to evaluate the biofidelity of the MADYMO model. The results revealed discrepancies in both force and displacement responses between the MADYMO model and PMHS, highlighting the model's limitations in accurately simulating human kinematics under crash conditions. Factors contributing to these discrepancies include simplified contact models, spinal stiffness, and the initial configuration of the spine. While MADYMO can provide consistent trends, its computational affordability comes at the cost of precision, necessitating future improvements in model fidelity. This research emphasizes the need for improved HBM to better represent the complexities of human biomechanics in reclined seating during vehicle collisions.

Keywords Reclined Seat, MADYMO Human Body Model, PMHS, Biofidelity, Kinematic Response

I. INTRODUCTION

Occupants in reclined seats face substantial safety risks in a road traffic accident. Dissanaike *et al.* [1] performed statistical analyses using two databases (CIREN and NASS/CDS) and discovered that fully reclined seats correlate with a heightened mortality rate. Schaefer *et al.* [2] also revealed that the injury risk for occupants in reclined seats is significantly elevated at MAIS levels 2+, 3+ and 4+ in comparison to those seated in an upright posture. Consequently, [2] concluded that reclined occupants have a higher risk of injury in traffic accidents.

To evaluate the crash responses of occupants in a reclined posture, Richardson *et al.* [3] from the University of Virginia (UVA) conducted frontal crash tests with five post-mortem human subjects (PMHS). The restraint system included a semi-rigid seat with adjustable seatpan stiffness and an integrated three-point seatbelt. The reclined seating posture compromised the effectiveness of the seat and belt restraint, leading to suboptimal kinematic response and an elevated risk of injury. Specifically, the initial posterior pelvic tilt predisposed the PMHS to submarining, while the spine experienced combined flexion and compression loads. As a result, all PMHS sustained rib and sternal fractures; four PMHS exhibited sacrococcygeal and iliac wing fractures; and three PMHS suffered lumbar spine fractures. These findings emphasise pelvic and lumbar spine injuries in reclined occupants and provide important data support for building simulation models.

To evaluate the biofidelity of three human body models (HBMs) in simulating frontal crashes with reclined postures, [4] employed three state-of-the-art HBMs: GHBMC v.6.0, THUMS v.6.1, and SAFER v.10. The study simulated frontal crashes at a 50° seatback tilt angle using a simplified environmental model that included a semi-rigid seat and a three-point seatbelt equipped with dual tension pretensioners. These HBMs differed in localised geometries, such as pelvic shape and lumbar vertebral alignment. Overall, these HBMs performed similarly, but varied in their predictions of the Z-direction motion. All HBMs predicted greater downward motion of the head and T1 vertebra compared to the PMHS. Furthermore, all HBMs exhibited posterior rotation of the pelvis at belt's peak load, while the PMHS displayed a slight forward rotation. Some researchers believe these discrepancies may be related to the lumbar flexion model and the soft tissue definition of the pelvis. These HBMs provide relatively accurate kinematic responses, but are computationally expensive. For large matrix simulations and analyses, Mathematical Dynamic Simulation Model (MADYMO) is a computationally affordable software tool widely used for the study of occupant safety in vehicle crashes.

However, there is currently a lack of correlation between the kinematic responses of the MADYMO HBM in a reclined posture and the experimental data from PMHS studies. This study used a MADYMO HBM to establish a simulation environment for analysing crash safety of reclined occupants in frontal collision. The kinematic responses of the occupant were compared with data obtained from PMHS experiments to preliminarily evaluate the biofidelity of the MADYMO model.

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II. METHOD

To evaluate the effectiveness of MADYMO in simulating the kinematic responses of reclined occupants, the same test conditions used in [3] were set up in the MADYMO simulation environment, as follows.

The sled pulse is the same as that employed by [3] in PMHS, as shown in Fig. 1.

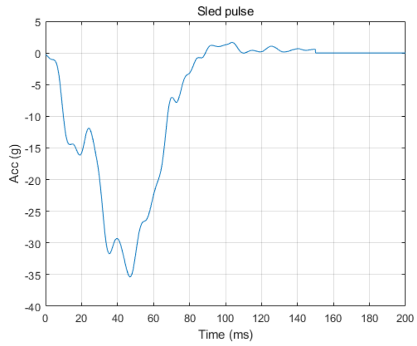


Fig. 1. Sled pulse used in MADYMO simulation.

The seat utilised in the PMHS test was a semi-rigid seat designed to replicate the response of a genuine automobile seat. In MADYMO, the semi-rigid seat is simplified into two rigid planes: the seatpan and the anti-submarining pan. The seatpan and anti-submarining pan are oriented as shown in Fig. 3. The stiffness of the semi-rigid seat is provided by springs that are hinged to it, which can be represented as the equivalent rotational stiffness of the pan around the hinge axis (Fig. 2). The seat stiffness data are adopted from a semi-rigid seat developed by [5]. The stiffness of the human pelvis deformable and the contact surface of the seatpan are configured as rigid contacts.

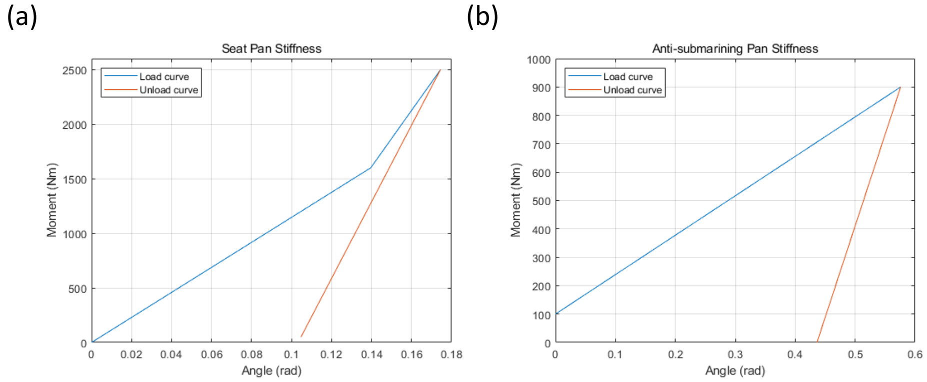


Fig. 2. Mechanical properties of semi-rigid seat cushions: (a) seatpan and (b) anti-submarining pan.

The human body has forward inertia during the frontal collision, and therefore the seatback model is omitted from the analysis. The seatback is only used during the pre-simulation in order to get the initial position of the model joint.

The model utilises a three-point seatbelt model from the MADYMO library. The shoulder-belt pretensioner and outboard lap-belt pretensioner are activated at 10 ms, while the inboard lap-belt pretensioner is activated at 3 ms. All pretensioners are equipped with a load limiter set at 3.5 kN. The positions of the D-ring, buckle, and anchor are consistent with those used in the PMHS experiments, as shown in Fig. 3(a). In the simulation, the feet of the human model are placed on a footrest, whereas in the PMHS the subjects' feet are fixed to the footrest.

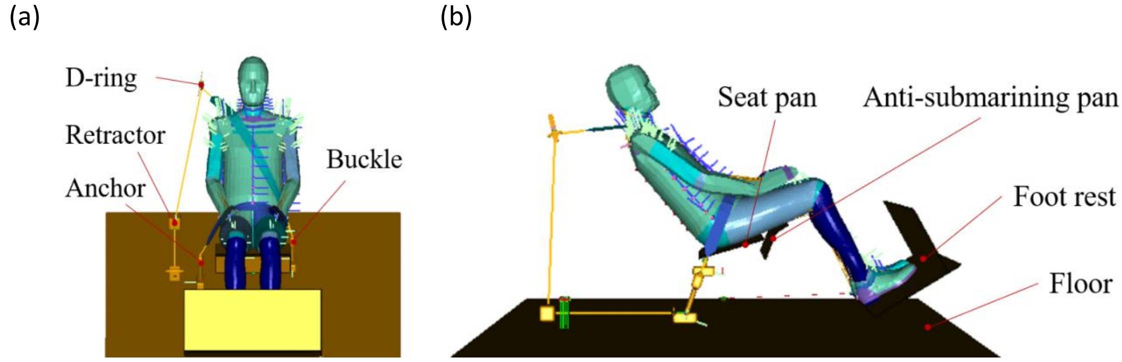


Fig. 3. Simulation models with different viewpoints.

The human model utilised in this study is the 50th percentile Active Human model from the MADYMO library, with a height of 176 cm and a weight of 75.3 kg. The active human model features a more detailed finite element (FE) mesh for the legs, providing a more realistic interaction with the simplified semi-rigid seat surface. The active behaviours were disabled during the simulation.

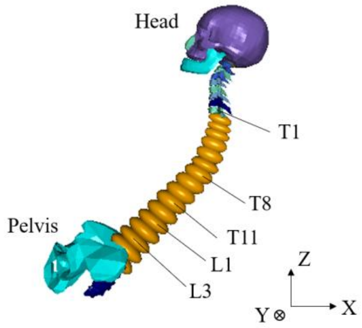


Fig. 4. Initial configuration of the spine.

TABLE I
INITIAL PITCH ANGLES OF THE SPINE

Part	Head	T1	T8	T11	L1	L3
Angle (deg.)	31	12	32	38	41	45
PMHS #930 (deg.)	59	7	43	58	60	51

The locations of the H-point and torso sagittal in the HBM are based on data of the PMHS #930 from the PMHS experiments [3]. Table I presents the initial pitch angles of the spine, indicating differences when compared to the spinal structure of PMHS. Both MADYMO model and PMHS exhibit a torso angle of 47 degrees.

III. RESULTS

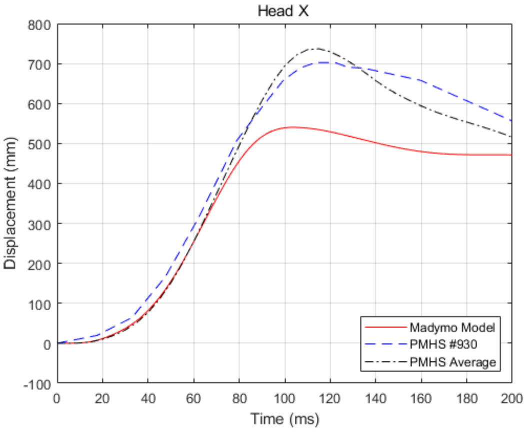
When a collision occurs, the seatbelt pretensioner is activated first, eliminating the gap between shoulder belt, lap belt, and occupant's body. As the collision progresses, the occupant's pelvis moves forward, pressing down on the semi-rigid seat. Meanwhile, the torso of the occupant moves forward, accompanied by pitching rotation. After the pelvis reaches its maximum displacement, it rebounds, followed by the rebound of torso. Table II shows the responses of the restraint in the MADYMO model and comparison with that of the PMHS test.

TABLE II
RESTRAINT RESPONSES AND CORRESPONDING TIMES

Restraint Device	Parameter	MADYMO	PMHS #930
Shoulder belt	Max. Force (N)	3376	3654
	Time (ms)	102	108
Lap belt	Max. Force (N)	6333	7968
	Time (ms)	71	58
Buckle	Max. Force (N)	10410	9698
	Time (ms)	58	60
Shoulder belt	Spool-out (mm)	116	349
	Time (ms)	97	109
Lap belt	Spool-in (mm)	7	20
	Time (ms)	11	15
Buckle	Displacement (mm)	33	55
	Time (ms)	32	10
Seatpan	Rotation angle (deg.)	9.4	10.3
	Time (ms)	61	63
Anti-submarining pan	Rotation angle (deg.)	6.8	10.3
	Time (ms)	54	70

Seat Force	Max. X-force (kN)	7.4	6.8
	Time (ms)	42	69
Seat Force	Max. Z-force (kN)	10.7	14.1
	Time (ms)	64	61

(a)



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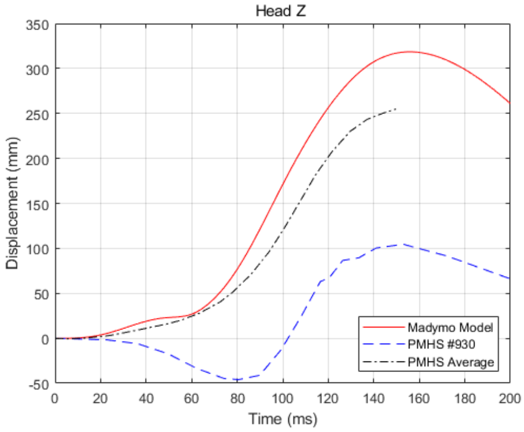

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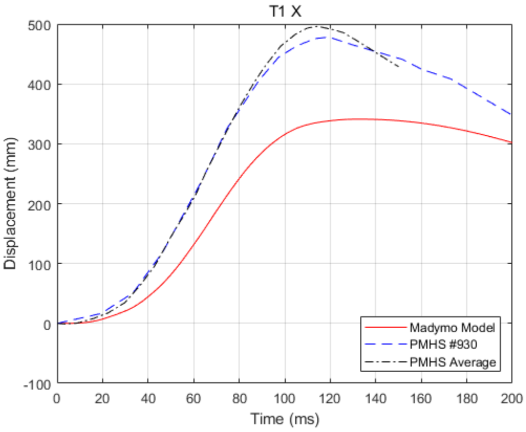

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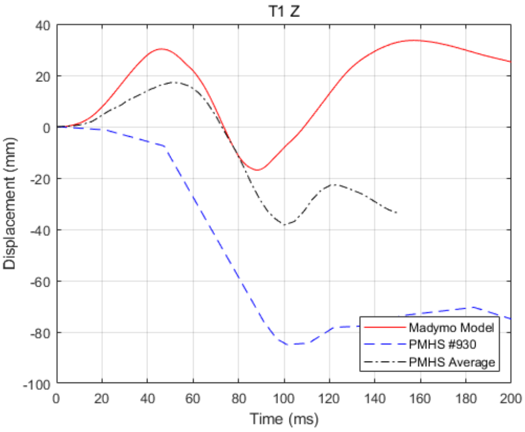

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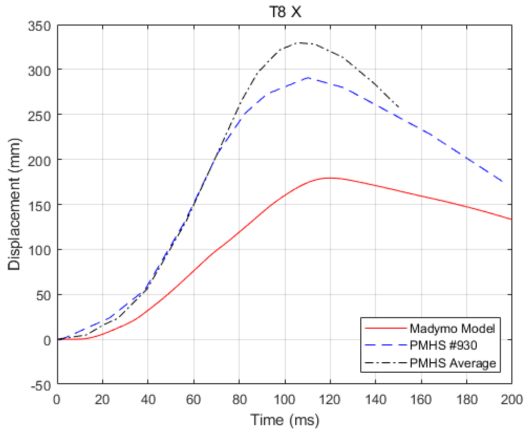

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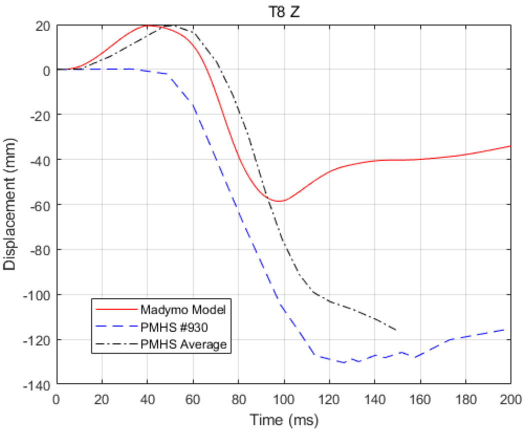

Fig. 5. Displacement of Head, T1, T8 in the X- and Z-directions.

The peak forces of the shoulder belt and lap belt in the model (3376 N and 6333 N) are both lower than those in the PMHS test (3654 N and 7968 N). Additionally, the spool-out of the shoulder belt in the model (116 mm) is significantly lower than that of PMHS (349 mm). Small extension of the seatbelt also affects the X-direction displacement of the torso. The X-direction displacements of the head and T1/T8 vertebrae of the occupant are approximately 200 mm smaller than that of the PMHS. The Z-direction displacement is closer to the average PMHS.

Although MADYMO can provide relatively consistent trends in kinematics, its deviations in force and displacement may reduce its effectiveness in safety assessments. The significant differences in kinematic responses indicate that the model needs to be improved to enhance its accuracy.

IV. DISCUSSION

Several factors contribute to the discrepancies observed between the MADYMO model's kinematic response and the PMHS tests' responses. These include simplified contact model, torsional stiffness of the spine, simplified representation of the spine and the effect of the initial spine configuration.

First, the semi-rigid seat is simplified as rigid planes and the corresponding stiffness curve. It leads to the interaction between the seat and the occupant's thigh relying more on the contact force model. Consequently, the extent of the penetration between the seat cushion and the thigh depends on the chosen contact characteristics. Such a simplified contact model between the pelvis and the cushion likely contributes to the unrealistic kinematic response.

While the seatbelt pretensioner force levels align reasonably well with the PMHS experiments, the significantly smaller belt spool-in suggests that the model's mechanical properties, from skin to skeleton, are excessively stiff. In reality, the seatbelt distributes force across the skin surface, whereas the model may overestimate the contact force and thus transfer greater force directly to the ribs and pelvis.

Further limitations arise from the HBM itself. The MADYMO spine's lower torsional stiffness also contributes to the discrepancies. This results in exaggerated forward shoulder movement on the unbelted side during the collision, increasing pitch rotation. This rotational component, in turn, reduces the forward displacement of the trunk, creating a significant difference compared to the PMHS experiments.

The use of rigid ellipsoids and simplified joint connections in the MADYMO model fails to capture the complexity of real sacral bones, intervertebral discs, and other vertebral structures. This simplification prevents accurate modeling of the spine's dynamic behaviour under load. The model's reliance on pre-set torque and angle curves for spinal mechanical properties, rather than dynamically responding to external forces as a real spine would, further compromises the accuracy. The initial spinal configuration also plays a critical role; real-world spinal forces and movement patterns vary significantly with posture, influencing injury risk. The MADYMO model's inability to adequately represent these postural influences contributes to the observed deviations.

In conclusion, while the MADYMO simulation provides consistent trends in kinematic response, its limitations should not be underestimated. Simplifications in the mechanical properties of the spine and contact models prevent accurate reflection of the reclined human body's dynamic response during frontal collisions. The model's inadequate representation of initial spinal configuration further exacerbates these inaccuracies. To improve simulation accuracy, future research should focus on refining the model's structural details to more realistically simulate the complex kinematic response in collisions. This includes improvements to the seat and pelvic contact models and more sophisticated representation of spinal anatomy and biomechanics.

V. ACKNOWLEDGEMENTS

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