Predicting the results of the finite element simulation of a snowboarding backward fall with ODYSSEE

Wei wei[1], Dorian Salin[2], Nicolas Bailly[1]

[1] Aix Marseille Univ, Univ Gustave Eiffel, LBA, Marseille, France
[2] CADLM part of Hexagon, Wissous, France

1 Introduction

Skiing and snowboarding are very popular sports, associated with a high risk of injury (2.35/1000 skiing days in 2019 in France [1]). Among those injuries, the leading cause of death is the head injury which accounts for 5-10% of all injuries. Several studies have shown that helmet was effective in reducing the risk of head injury [2], [3] but the effect of the helmet in reducing certain types of brain injuries such as concussion is still unclear [4], [5]. To better evaluate and design effective helmets, it is critical to understand the head impact condition during the crash as well as the injury mechanism.

In snowboarding, the leading cause of traumatic brain injury was identified by Nakaguchi et al. [6] as a backward fall induced by the back edge of the snowboard catching the snow slope. This type of fall results in an impact of the head against the snow in the occipital region leading to mild and severe brain injury. Several studies have looked at the head impact conditions (head impact speed, force, and acceleration) during this type of crash. The snowboarding backward fall was first reproduced by Scher et al. [7] using an instrumented 50th percentile male Hybrid III anthropomorphic test device providing the first insight on the dynamic of the fall. Bailly et al. and Wei et al. then reproduced hundreds of crashes scenarios using the fast and robust multibody simulation method, in order to quantify the range of head impact conditions [8], [9] depending on the parameters of the crash (initial velocity, stiffness of the snow, size, and position of the snowboarder). These studies provided valuable information on the impact conditions - necessary for the design and evaluation of protections - but were unable to provide precise information on injury mechanisms such as local brain strain and spine loadings.

The use of human finite element (FE) model would enable to access that information and to evaluate the effect of helmet design on head injury prevention. Several head and brain models have been developed, validated, and used to reproduce head impacts. These models provide a more reliable injury prediction than the head kinematic criteria as well as insight on the injury mechanism (localized stress and strain in various parts of the brain) [10]–[12]. In particular, the THUMS models have been developed, validated, and used to reproduce automotive crashes and predict traumatic brain injury [13]–[15]. Several researchers have combined the fast and robust multibody simulation with FE modeling: they reproduced with FE modeling the head impact condition obtained with multibody simulations of the full accident [15]–[17]. However, this method is costly and time consuming and thus not suitable to reproduce hundreds of impact scenarios and evaluate helmet design.

Model Order Reduction (ROM) techniques are interpolation methods exploiting existing datasets (input and output) derived from an existing model or experimental setup. The starting point is a Design of Experiments (DOE) which covers as much as possible the design space (space filling property). Contrary to response surface (polynomial based) designs where the selection of design points at particular positions is important due to a-priori properties of the fitted surface, for ROM techniques, the most important issue is the space-filling capacity and sufficient “modal” representation of the response. ROM has been used in various cases of crash and ALE [18]–[21] and have proved their capability to produce accurate results in real-time with a reasonable amount of learning data. Such a technique suits for creating real-time applications based on long and voluminous FE simulations such as snowboarding falls.

The purpose of this study was therefore to propose and evaluate a method coupling a FE Human model (i.e. THUMS) with a ROM technique from ODYSSEE [19] to provide a real-time analysis of the head impact in snowboarding backward falls.

2 Materials and methods

The method consists in evaluating if the ROM technique from ODYSSEE can predict the result of FE modeling of any head impact during snowboarding backward falls. In the following sections, we will present (a) the expected range of head impact condition during snowboarding backward falls, (b) the FE simulations of these impacts, (c) the prediction of the FE simulation results by ODYSSEE.

2.1 Head impact conditions in a snowboarding backward fall

The head impact conditions were extracted from the 324 multibody reconstructions of snowboarding backward falls in Bailly et al. study [8]. In those simulations the impact occurs between the occipital region of the head and the snow ground. Three parametters were used to described the head impact conditions : the normal impact velocity (Vn), the tangential impact velocity (Vt) and the sagittal head impact angle (α) relative to the snow ground. The ranges of those three parameters chosen for the study are presented in table 1.

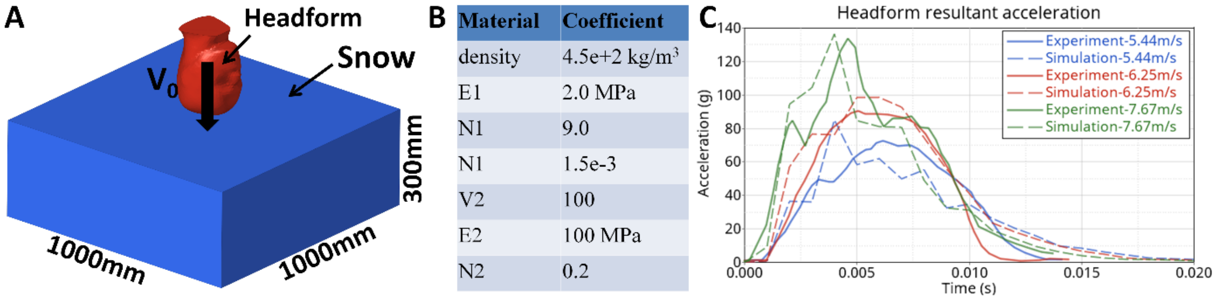
	Min	**Max**
Normal impact speed (Vn) ($m.s^{-1}$)	3	5.5
Tangential impact speed (Vt) ($m.s^{-1}$)	7.9	10.3
Impact angle (α)	20	65

Table 1: Range of the head-to-snow impact conditions

2.2 Finite element modeling of head impact

2.2.1 The FE modeling of snow ground

The head of the snowboarder impacts a snow ground which deforms and absorbs some of the impact energy. To adequately reproduce the impact, published experiments testing mechanical properties of snow in dynamic loadings were reproduced numerically to calibrate the material properties of the snow in the FE simulation. The experimental test consisted of drop tests of a rigid standard head form (6kg in mass) at 5.44m/s, 6.25m/s, and 7.67m/s on hard snow [8] in which the head acceleration was recorded. In the numerical reproduction, the standard head form was modeled as a 6kg rigid body with 2D shell elements. The layer of snow with the size 1000mm*1000mm*300mm was modeled with 6-node hexahedron elements and with viscous foam material law (Figure 1.A). The initial parameters of the material law were defined according to Mellor et al. [22]. An optimization-based procedure was then used to find the best parameters to minimize the differences between the numerical head accelerations and the experimental accelerations for the three impact velocities (i.e. 5.44m/s, 6.25m/s, and 7.67m/s). The initial and optimal parameters, are presented in Figure 1.B and the comparison between the experimental and numerical head acceleration with the optimal parameters are presented Figure 1.C.

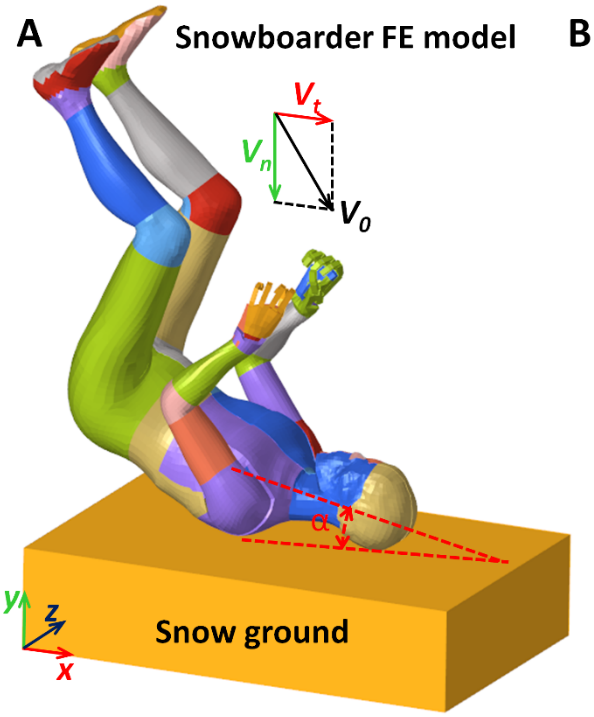


Material	**Coefficient**
density	4.5e+2 kg/m^3
E1	2.0 MPa
N1	9.0
N1	1.5e-3
V2	100
E2	100 MPa
N2	0.2

Fig.1: (A) FE model set up for head form drop test on hard snow; (B) material coefficients for the hard snow; (C) validation of numerical head form accelerations

2.2.2 The FE modeling of the snowboarder

The Total Human Model for Safety (THUMS) v5.03 AM50 (1.78 m, 78.2 kg) occupant model was used to model the snowboarder impacting the snow surface (figure 1). The THUMS model was selected because of its robustness and of its wide range of validations, in particular regarding the brain deformation at impact [13], [15], [23], [24]. To limit the effects of the limbs' movement on head-neck responses during the impact, the joints of the limbs (e.g. wrist, elbow, knee, ankle, etc.) were fully constrained in the simulations. The THUMS model was positioned close to a supine posture with the head slightly above the snow ground (Figure 2.A) with an angle (α) between the craniocaudal axis of the THUMS and the tangential axis of the ground. The THUMS was projected on the snow surface with an initial tangential velocity (Vt) and an initial normal velocity (Vn) relative to the ground (Figure 2.A). The head-to-snow impact was modeled for a duration of 100 ms which was enough to fully capture the contact between the head and the snow. During the impact, we recorded the head acceleration, the maximal principal strain in the brain (MPS) and the cervical vertebral cross-section force in the C1 vertebrae. All the FE simulations were performed with the explicit solver in LS-DYNA 971 R11.1 (LSTC. Livermore, CA, USA) on an Intel Xeon (2.20 GHz) workstation with 24 processors.



B

Dataset	ID	Vt (m/s)	Vn (m/s)	α (degree)
Baseline	1	3.00	9.93	23.91
	2	3.31	8.08	41.52
	3	3.63	9.56	59.13
	4	3.94	8.82	29.78
	5	4.25	10.30	47.39
	6	4.56	7.90	65.00
	7	4.88	9.38	20.00
	8	5.19	8.64	37.61
	9	5.50	10.12	55.22
Validation	10	4.80	9.94	25.00
	11	4.33	8.32	40.00
	12	3.50	9.08	50.00

Fig.2: (A) FE model setup for snowboarder head-to-snow impact; (B) initial impact condition settings for the baseline and validation simulations

2.3 Evaluation of ROM capability in predicting the FE simulation results

In order to cover the 324 scenarios of snowboarding backward falls, and because FE simulation requires a lot of computational resources, it is necessary to be able to estimate biomechanical loading levels in a more efficient way. ROM method is a non-intrusive reduction method that allows to predict time-dependent responses in real-time based on past experiments (Figure 3).

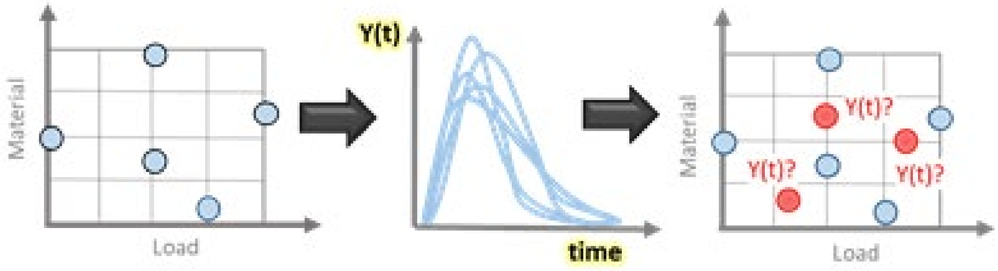


Fig.3: The ROM method

Based on this, a Hammersley method was used to define a DOE with 9 impact conditions (baseline) covering the range of those 3 parameters (Figure 2.B). Three additional impact scenarios (validation), chosen within the range of the three parameters were also reproduced using the THUMS Model for validation (Figure 2.B). The maximal principal strain (MPS) in the brain as well as the loading force in the cervical vertebrae C1 of the first 9 simulations (baseline) were extracted and used in ODYSSEE to predict those of the three other simulations (validation). The MPS, and vertebral loading curves predicted by lunar were compared to those obtained by the FE simulations using mathematical criteria such as the coefficient of determination (R2).

3 Results

Twelve impact scenarios were simulated (9 for the model and 3 for validations). The time of 1 simulation was approximately 10 h on an Intel Xeon (2.20 GHz) workstation with 24 processors. All three parameters had a significant effect on the force in the C1 vertebrae, but this force was most affected by Vn and α. Figure 4 presents the comparison between the loading forces measured in the C1 vertebra of the THUMS model and the force in C1 predicted by ODYSSEE in the 3 tested impact conditions: Lunar closely predict in real time the force curve with an R2 (coefficient of determination) of 79.8, 88.0 and 82.0 for the cases 1, 2 and 3 respectively.

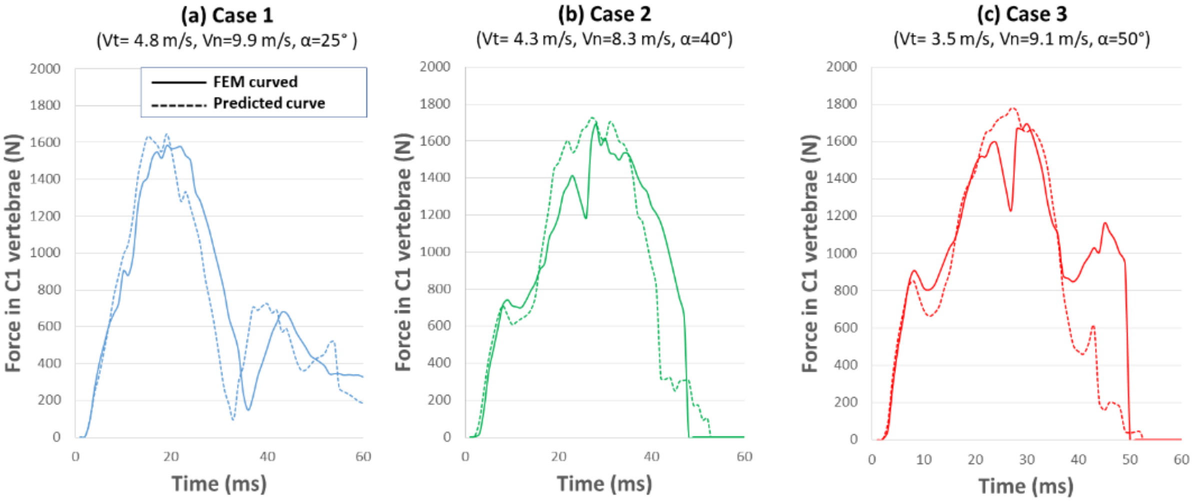


Fig.4: Comparison between the force measurement in the C1 vertebra of the THUMS model and the force in C1 predicted by ODYSSEE

Figure 5 presents the comparison between the maximum MPS in the brain of the THUMS model and the MPS in the brain predicted by ODYSSEE in the 3 tested impact conditions: Lunar predicted in real time the MPS with an R2 (coefficient of determination) of 84.8, 79.7 and 88.0 for the cases 1, 2 and 3 respectively. Signals were cut down 40 ms after the impact because of chaotic behaviour after this moment. Indeed a third rebound in brain strain was visible in some head impact conditons but not on the others: additional baseline data from simulations are needed to be able to correctly predict the brain strain after this stage.

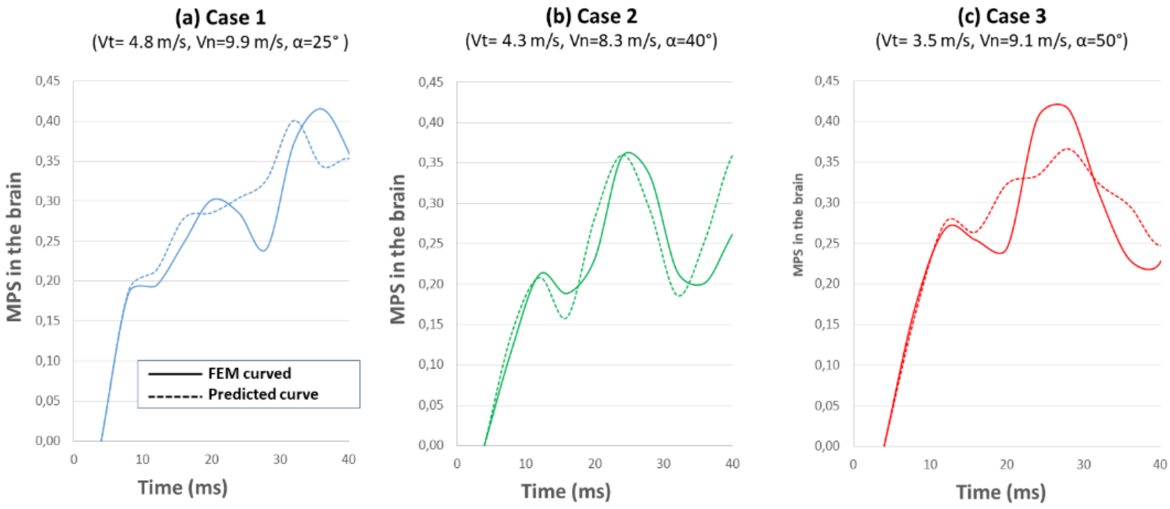


Fig.5: Comparison between the maximum principal strain (MPS) in the brain of the THUMS model and the MPS in the brain predicted by ODYSSEE

4 Discussion

In this paper, the use of FE modeling to complement multibody modeling enable access to precise information on the injury mechanisms such as local brain and spine loadings. With this combined modeling, we were able to compute information on impact conditions and injury mechanism based only on parameters of crash such as velocity and posture before the crash. For instance, the reproduction of a snowboarding backward fall of a 50 percentile male going at a speed 30km/h showed normal head impact speed up to 10 m/s and both brain strain and force in C1 higher than published threshold for injury. This combined modeling is thus a powerful tool to investigate crashes as well as to evaluate and to develop protections. However, this method is very costly (approximately 10h of calculation) and thus not practical to investigate various crash scenarios.

This paper also evaluates the use of ROM method with ODYSSEE to obtain the FE simulation results in real time. Results shows that the method provides a good level of accuracy (R2>79) with only 9 learning simulations for a wide range of impact conditions. It can thus be used to investigate the injury mechanism in snowboarding crashes in various crash scenarios within the validation range. By strongly reducing the calculation times, the ROM methods enable the use of detailed biomechanical model for investigating a large set of crash scenarios and open up numerical design and evaluation of protective devices.

5 Conclusion

The use of ROM methods was adequate to predict tissue-level loadings of the THUMS model during a snowboarding backward fall. The method can highly reduce the calculation time as it gives results in real time and requires only a small sample of simulations for learning. This work is a proof of concept that the methodology could be used on detailed biomechanical model and open up numerical design and evaluation of protective devices. Thanks to LS-DYNA/QUASAR coupling, some part of the model, such as the Thums model, could also be replaced in the future by a reduced order model inside the LS-DYNA model.

6 Summary

Snowboarding backward fall is the most common crash scenario leading to brain and spinal injury on the ski slopes. Previous work reproduced hundreds of crash scenarios using the multibody simulation method, highlighting a range of head impact conditions but unable to identify local brain and spine loadings. The use of human finite element (FE) model would enable to access that information but is too time-consuming to reproduce hundreds of impact scenarios. The purpose of this study was to couple a Human FE model with a Reduced Order Modelling (ROM) technique from ODYSSEE to provide real-time analysis of the snowboarding backward fall. The range of the normal (Vn) and tangential (Vt) impact velocity and of head impact angle (α), were extracted from 324 multibody reconstructions of snowboarding backward falls. A Hammersley method was used to define a design of experiments (DOE) with 9 impact conditions covering the range of these 3 parameters. These impact conditions were reproduced using the THUMS v5.03 M-50 occupant model impacting a snow ground on the LS-DYNA 971 R11.1 solver. Three additional impact scenarios were also reproduced for validation. The maximal principal strain (MPS) in the brain and loading force in C1 vertebrae of the first 9 simulations were used in ODYSSEE to predict those of the 3 other simulations. The predicted results were compared to FE simulation results. ODYSSEE closely predicted in real-time the curve of the force in C1 for the 3 validation cases (R2>79). This work is a proof of concept that the methodology could be used to reduce the calculation time on a detailed biomechanical model and open up numerical design and evaluation of protective devices.

7 Literature

[1] Association des Médecin de Montagne, “Dossier de presse de l’accidentologie des sports d’hiver saison 2019-2020,” 2021. [Online]. Available: http://www.mdem.org/france/STATISTIQUE/page/Accidentologie-des-sports-d-hiver.html

[2] Sulheim S, Holme I, Ekeland A, and Bahr R, “Helmet use and risk of head injuries in alpine skiers and snowboarders,” *JAMA*, vol. 295, no. 8, pp. 919–924, Feb. 2006

[3] K. Russell, J. Christie, and B. E. Hagel, “The effect of helmets on the risk of head and neck injuries among skiers and snowboarders: a meta-analysis,” *Can. Med. Assoc. J.*, vol. 182, no. 4, pp. 333–340, Sep. 2010

[4] T. Dickson, S. Trathen, F. Terwiel, G. Waddington, and R. Adams, “Head injury trends and helmet use in skiers and snowboarders in Western Canada, 2008–2009 to 2012–2013: An ecological study,” Scand. J. Med. Sci. Sports, vol. 27, no. 2, pp. 236–244, 2017.

[5] N. Bailly *et al.*, “Effect of helmet use on traumatic brain injuries and other head injuries in alpine sport,” *Wilderness Environ. Med.*, 2018.

[6] H. Nakaguchi, T. Fujimaki, K. Ueki, M. Takahashi, H. Yoshida, and T. Kirino, “Snowboard head injury: prospective study in Chino, Nagano, for two seasons from 1995 to 1997,” *J. Trauma Acute Care Surg.*, vol. 46, no. 6, pp. 1066–1069, 1999.

[7] I. Scher, D. Richards, and M. Carhart, “Head injury in snowboarding: evaluating the protective role of helmets.,” *J. ASTM Int. JAI*, vol. 3, no. 4, 2006

[8] N. Bailly, M. Llari, T. Donnadieu, C. Masson, and P.-J. Arnoux, “Head impact in a snowboarding accident,” *Scand. J. Med. Sci. Sports*, vol. 27, no. 9, pp. 964–974, 2017.

[9] W. Wei, M. Evin, N. Bailly, M. Llari, J. Laporte, and P. Arnoux, “Spinal injury analysis for typical snowboarding backward falls,” *Scand. J. Med. Sci. Sports*, vol. 29, no. 3, pp. 450–459, 2019.

[10] C. Deck, N. Bourdet, F. Meyer, and R. Willinger, “Protection performance of bicycle helmets,” *J. Safety Res.*, vol. 71, pp. 67–77, Dec. 2019

[11] S. Meng, A. Cernicchi, S. Kleiven, and P. Halldin, “High-speed helmeted head impacts in motorcycling: A computational study,” *Accid. Anal. Prev.*, vol. 134, p. 105297, Jan. 2020

[12] M. Fahlstedt *et al.*, “Ranking and Rating Bicycle Helmet Safety Performance in Oblique Impacts Using Eight Different Brain Injury Models,” *Ann. Biomed. Eng.*, vol. 49, no. 3, pp. 1097–1109, Mar. 2021

[13] F. Wang *et al.*, “Prediction of brain deformations and risk of traumatic brain injury due to closed-head impact: quantitative analysis of the effects of boundary conditions and brain tissue constitutive model,” *Biomech. Model. Mechanobiol.*, vol. 17, no. 4, pp. 1165–1185, Aug. 2018

[14] M. Lalwala, A. Chawla, P. Thomas, and S. Mukherjee, “Finite element reconstruction of real-world pedestrian accidents using THUMS pedestrian model,” *Int. J. Crashworthiness*, vol. 25, no. 4, pp. 360–375, Jul. 2020

[15] L. Shi, Y. Han, H. Huang, J. Davidsson, and R. Thomson, “Evaluation of injury thresholds for predicting severe head injuries in vulnerable road users resulting from ground impact via detailed accident reconstructions,” *Biomech. Model. Mechanobiol.*, vol. 19, no. 5, pp. 1845–1863, Oct. 2020

[16] N. Bourdet, C. Deck, T. Serre, C. Perrin, M. Llari, and R. Willinger, “Methodology for a global bicycle real world accidents reconstruction,” 2012, no. 2012–077, p. 10p.

[17] D. Montoya, L. Thollon, M. Llari, C. Perrin, and M. Behr, “Head injury criteria in child pedestrian accidents,” *Int. J. Crashworthiness*, vol. 23, no. 5, pp. 497–506, Sep. 2018
[18] K. Kayvantash, A.-T. Thiam, D. Ryckelynck, S. B. Chaabane, J. Touzeau, and P. Ravier, “Model Reduction Techniques for LS-DYNA ALE and Crash Applications,” presented at the Proceedings of 10th European LS-DYNA Conference, 2015.
[19] K. Kayavantash, “ODYSSEE (Quasra/Lunar) software package for Machine learning, Model fusion,Forecasting and.” Release 2017. [Online]. Available: www.cadlm.com
[20] Yasuki, T. : “Application of reduced model to estimating Nij of HYBRID3 AF05 dummy in sled FE simulation, DYNA conference, Salzburg, Austria, 2017
[21] Yasuki, T. : “Application of reduced Model to Simulations of Occupant Protection and Crashworthiness at Toyota”, Advanced CAE division, Toyota Motor Corporation, 15th International LS-DYNA Conference & Users Meeting, Detroit, USA, 2018
[22] M. Mellor, *A review of basic snow mechanics*. US Army Cold Regions Research and Engineering Laboratory Hanover, NH, 1974.
[23] M. Iwamoto, Y. Nakahira, and H. Kimpara, “Development and Validation of the Total HUman Model for Safety (THUMS) Toward Further Understanding of Occupant Injury Mechanisms in Precrash and During Crash,” *Traffic Inj. Prev.*, vol. 16, no. sup1, pp. S36–S48, Jun. 2015
[24] L. E. Miller, J. E. Urban, and J. D. Stitzel, “Validation Performance Comparison for Finite Element Models of the Human Brain,” *Comput. Methods Biomech. Biomed. Engin.*, vol. 20, no. 12, pp. 1273–1288, Sep. 2017