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Body part surrogates for safety research

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Abstract. Present paper outlines the advantages of experiments performed using human body part surrogates (physical models) in combination with virtual experiments carried out using numerical models for the medical studies, safety research and development of safety equipment. Material uses the examples of setups using instrumented human head and neck surrogates developed and constructed at Mid Sweden University, Sweden and the University of Padua, Italy.

I. Introduction

Significant progress has been achieved in the design and manufacturing of the trauma-protecting devices. Further improvements are continuously introduced capitalizing on better understanding of trauma mechanisms and introduction of novel materials and manufacturing technologies [1,2]. Present paper illustrates the advances in this field through introduction of experiments utilizing body part surrogates through the examples from traumatic brain injury (TBI) prevention research.

II. Modeling in safety research

All trauma-protecting devices should be thoroughly tested before use and in a variety of realistic situations. But testing of unproven devices with human subjects is out of question, and it is simply dangerous as the level of protection is initially unclear. In many similar cases research is turning to the analytical (mathematical) or computer (numerical) modeling [3,4]. Development of computer technology already allows for virtual experiments, where advanced models of human body parts are combined with the models of safety devices producing simulations of injury-threatening events in a large number of real-life scenarios. Here one capitalizes upon the known advantages of the modeling. Indeed, there is no danger to the humans or destruction of any equipment. There is a possibility to clarify the process dynamics (speeding or slowing the time in virtual world). Deeper understanding of most critical issues can be achieved in virtual experiments by switching on and off certain interactions and decoupling processes or parameters that are coupled in real world. All this allows for using the power of prediction provided by properly constructed models.

Unfortunately there are certain drawbacks associated with the modeling. Approximations and limitations of the scope are "built in" during the model development, as each model is constructed with certain purpose, and cannot cover all the detailed interactions and complexity of the real human subjects. In the numerical modeling additional errors coming from algorithm instability and discretization effects are also inevitable.

More issues are added as many input data demanded by the models are often unavailable and should be somehow "synthesized". Some of the parameter values needed for the modeling can be provided by animal experiments [5], but obvious restrictions and clear dissimilarities with human objects limit their applicability. Also, only scarce data exist from the cadaver experiments [6]. Additional problems for modeling are coming from the significant spatial variation of the properties of the human tissues, and very often their nonlinear static and dynamic responses.

Additional problem is due to one of the general rules of modeling, as the model cannot be "proven from inside". The only way of validating models is comparing their prediction results with the experimental data, which in case of human trauma research are scarce or not available. Progress in wearable devices allows for collecting the data on the dynamics of the body part motion in active sports, and experiments with crash dummies are definite ways forward (e.g. [7]). But the representation of human body parts provided by the crash dummies is not adequate for the validation of the advanced numerical models.

III. Advanced body part surrogates

One of the methods allowing for the collecting necessary experimental data in safety research is provided by the advances in manufacturing synthetic body part surrogates [8-10]. Such surrogates are also models, but the physical ones. Main advantages of their application are the same as for all models, with few valuable additions. Such surrogates can be significantly more complex as compared to the crash dummies, and often combine sections with different properties (bones, cartilage, soft tissues and bodily fluids). Thus experimental studies can be carried out in quire realistic scenarios. Embedded sensors allow for collecting dynamic experimental data on the relative motion of the parts, pressure, compression and tension inside the tissues. Similar miniature sensors can be attached to or embedded into the safety devices.

The inherent impossibility of validation of the physical model from itself is still present, but now two models, numerical and physical, can be cross-validated. The needed

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static and dynamic properties of the surrogate materials can be directly measured. The 3D geometries can be directly transferred between the models as common CAD files are used for 3D printing of the hard sections or for the molds for the casting of soft sections of surrogates. Also, the further modifications into the physical surrogates are not extremely complicated due to the flexibility of the additive manufacturing.

IV. Head-neck surrogates for TBI studies

For several year we are developing and improving the head-neck surrogates for the studies of the brain concussion mechanisms, and safety helmet development. Early prototypes were using Hybrid III neck from the crash test dummies (Figure 1).

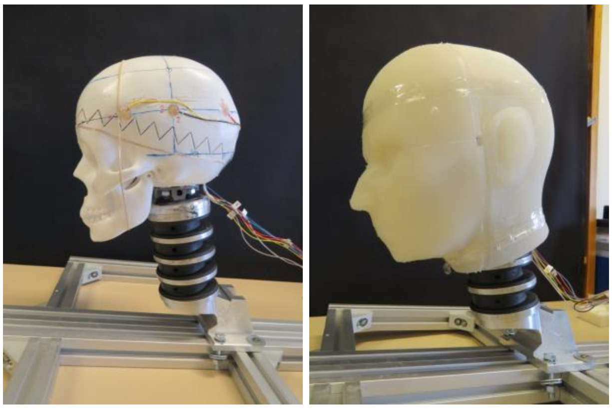

Figure 1: Setup for the pendulum-impact helmet testing using the Ssurrogate Head Prototype I and Hybrid III neck.

Head surrogate consists of the anatomically correct polymer scull filled with surrogate cranium fluid, surrogate brain cast from the soft rubber and outer “flesh and skin” cast from harder rubber. Cranium and lower jaw are directly 3D-printed, and soft tissues are cast in the 3D-printed molding forms. A number of miniature triaxial linear and angular acceleration sensors embedded into the surrogate brain monitor the dynamics of relative motion of the different tissue segments. Pressure sensors embedded into the cranium monitor the pressure waves in the cranial fluid [9, 10]. Additional motion sensors are placed at the chosen locations on or within the helmet. Fast data acquisition (up to 4000 times per second for all sensor channels) provide adequate time resolution for the signals generated during and after the impacts of the pendulum type hammer. Early comparison of the experimental results with the modeling have indicated the need for the improvements into the initial setup. New sensor for measuring the stress and strain in the brain surrogate was developed and incorporated into the new “head” version [11]. Later versions of the head surrogate were slightly scaled down, as initial design appeared to be large even for XL helmet sizes. Surrogates of arachnoid and dura mater were added. Oil appears to be more viscous than real cranial fluid and is substituted by the water-based surrogate. Latest setup was complemented by the polymer-based neck surrogate that is more flexible and biofidelic than Hybrid-III one. Latest head surrogate versions are modified allowing for the applications in the drop type tests, and impact tests with the Hybrid-III or newly developed biofidelic neck surrogates.

Resulting setups are intensely used for the new safety helmet development, comparison of helmet performance, and for studying TBI mechanisms in different impact scenarios. Combination of the sensors embedded into the body part surrogates and protecting devices allow for the analysis of the damping and energy absorbing properties of different safety helmets, supporting their more reliable impact testing and better certification.

V. Conclusions

Synthetic human body part surrogates have a significant potential for the advancements in the medical and safety research, complementing numerical modeling methods and allowing for the experimental data collection in the realistic scenarios. Complexity and biofidelity of such surrogates already allows for the in-depth studies of the dynamic processes leading to human trauma, and detailed analysis of the protection capacity of safety devices in a variety of different realistic scenarios. Flexibility of the 3D-printing methods actively used in manufacturing human body part surrogates not only provides high 3D-biofidelity, but will allow for the future individualized studies. Advances in the microelectronics already allow for manufacturing of the smart compact devices for crash helmets designed to alert users of the danger levels of impacts and crashes, and will allow saving the crash data vital for the better diagnosing of the injuries. Setups with described surrogates will be important for testing and certification of such devices.

Author's statement

Conflict of interest: Authors state no conflict of interest.

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