We are IntechOpen, the world’s leading publisher of Open Access books
Built by scientists, for scientists

6,600
Open access books available

177,000
International authors and editors

195M
Downloads

154
Countries delivered to

TOP 1%
Our authors are among the most cited scientists

12.2%
Contributors from top 500 universities

WEB OF SCIENCE™
Selection of our books indexed in the Book Citation Index in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com
Chapter

Body Part Surrogates for Medicine, Comfort and Safety Applications

Andrey Koptyug and Mikael Bäckström

Abstract

Body part surrogates made with support from additive manufacturing (AM) technologies belong to a rapidly developing area of modeling. Although computer-based and mathematical modeling of complex processes is already an established field, these are not free from inherited problems. Surrogate modeling (physical modeling) being a subject of its own successfully complement mathematical and computer modeling and helps to cross-validate these methods and improve particular models. Present chapter provides a discussion on the general aspects of modeling relevant to the design, manufacturing and application of body part surrogates. It also introduces new term ‘surrogate twins’ using the analogy of ‘virtual twins’. It also outlines a number of known applications of body part surrogates manufactured with support of AM in medicine, safety and comfort research. Strong and weak points of particular surrogate models is discussed basing on the general concepts of modeling including defining of particular surrogate model purposes, approximations, the ways of model validation, input parameter harvesting, related measurement systems and data processing, and setups for material and product testing. Comprehensive references will allow readers getting detailed information regarding discussed issues.

Keywords: additive manufacturing, body part surrogates, physical models, digital twins, surrogate twins, safety research, medical applications

1. Introduction

Body part surrogates made with a support from additive manufacturing technologies belong to a new rapidly developing dimension in modeling, linking theories to experimental science (e.g. [1–3]). Current developments in corresponding approach and technology of physical modeling constantly bring in new applications. Present contribution is focusing at the applications of such surrogates ranging from comfort and safety research to the medicine and traumatology.

It is intuitively clear that testing or manufacturing novel safety devices without somehow proving them being safe is not possible. Two dominant ways out from this “catch 22” situation are either through developing advance computer models of human body, its parts and safety devices allowing “virtual experimentation” in close to real conditions, and experimenting with physical models having different degree of fidelity, such as for example car crash dummies and their elements. Although
computer-based and mathematical (analytical) modeling of complex processes is already an established field, these are not free from problems. In relation to biomedical, comfort and safety research, where the subjects (human) are extremely complicated dynamic systems, inability to prove the model from within a model and potential dangers in direct experimental validation cannot be easily overcome. Physical modeling helps to expand the possibilities towards real experiments with human body part surrogates allowing cross-validation of the results of both modeling approaches. Well established and standardized car crash dummies and their separate elements, such as ‘head’ and ‘neck’, find wider applications for example in protection helmet design and testing, but in many cases are not optimal for lower energy impacts. Developing physical models of human body parts (body part surrogates) with improved biofidelity is one of the fast developing trends rapidly widening possible application areas. Additive manufacturing and modern sensor application are the main enabling elements in such developments.

Modern additive manufacturing (AM) technologies often referred to as 3D printing allow for the manufacturing of the body part surrogates with high fidelity in both 3D geometry and properties. When supplemented by a number of embedded sensors—providing valuable static and dynamic data they form a basis for powerful setups and platforms for research and device testing. Such surrogates can be subjected to a ‘serious abuse’ replicating real world situations either dangerous or potentially leading to injuries, and allowing for the qualitative and quantitative assessment of the protection and for testing wearable devices and different apparels.

Development of the computer technology and in particular virtual representation allows for advanced modeling of extremely complicated systems [4, 5] enabling unprecedented level of details and yielding so-called ‘digital twins’ (for example, applied in technology [6–8], medicine [9], safety research [10–13] and garment fitting [14]). However, such computer-based representations cannot be proven from within themselves, and are in need of experimental validation. Although certain information about the performance of already existing safety devices or even unfortunate consequences of some events leading to injuries can be used for validation more experimental data is needed. Manufacturing of the advanced sensorized human body part surrogates allowing for acquisition of needed experimental data in physical modeling it is already approaching such level of complexity and fidelity that corresponding surrogates can be termed ‘surrogate twins’.

Understanding the relations between ‘digital twins’, ‘surrogate twins’ and the human subjects they are designed to represent, demands some deeper analysis of pros and cons of modeling in general. So following material intends to discuss such aspects and supplement these with particular examples of applying computer and physical modeling (body part surrogates) in safety research.

2. Relevant general concepts of modeling

Although many people are using modeling in everyday practice, defining it one would commonly refer to certain specific modeling subject or approach. Given definitions commonly range from ‘a representation of a system using general rules and concepts’, ‘a physical representation in three dimensions of an object’, ‘a representation of a system using mathematical concepts and formalization’ to a ‘simulation to reproduce a behavior of a system, and ‘a formalized description of the world, its shapes, phenomena and processes happening in it’ among others.
Unfortunately, the comprehensive analysis of the very basic and general modeling concepts is still not easy to find in the literature. However, one of the best concise sets of relevant definitions and basic concepts was developed by Roger D. Smith in his ‘Fundamental principles of Modeling and Simulation’ [15], where he is introducing basic terms, concepts, techniques, and applications of modeling from the philosophy of science perspective. He stresses that a model is designed to serve a certain specific purpose, and has certain limitations ‘built in’ when it is constructed and developed. Consequently, it is hard to expect a model to be universal and to cover all imaginable cases and situations. It is also inherent to all models that they are using certain approximations of the real systems and processes happening in them. Proper modeling always starts with relatively simple and in a way ‘rough’ approximations aiming at most important system features. When such most critical features are adequately represented, the features assumed to be of ‘second order of importance’ are introduced to improve the model. It is well known that unnecessary complicating the model contrary to the obvious assumptions can reduce its applicability: relations become obscured, conclusions become hard to comprehend, and large amount of details buries the trends. It becomes a situation when it is hard ‘seeing the forest for the trees and leaves’. Thus, term adequacy in relation to the models means that a model uses just enough details to serve the initial purpose of its construction. When the model in its initial shape is validated, and successfully used, it is possible to expand it adding more details after finding that some of the effects, interactions, components are not represented to adequate precision or level of detail. In such expansion process ‘necessity rules’, exactly as it was when the basic model was constructed. Thus, well known ‘Occam’s razor’ principle, declaring, “entities should not be multiplied beyond necessity”, is equally applied in constructing and expanding/improving models.

Related to the discussed subjects, we assume that models we would like to construct are made with a certain purposes including studying complicated system and dynamics of the processes involved, to understand its functioning in different but well-defined conditions, to grasp interrelations of its parts in order to make certain predictions (e.g. [1–3, 16]). Thus, one needs to treat both physical and mathematical modeling of human body parts from the points of view of intended purpose, predictive capacity as well as strong and weak points and restrictions inherent in such models.

3. Aspects of modeling relevant to medicine, safety and comfort research

Although experiment is one of the bases for scientific research, real experimenting with human subjects has obvious limitations. One issue is due to the differences between individuals, leading to the need in collecting large amount of data from different subjects followed by statistical analysis in order to get generalized representation. In addition, in many situations experiments can be potentially dangerous or harmful, or not possible due to certain ethical reasons. Medicine and safety research are very typical in this respect. A lot of information about functioning of human body and its parts was collected through treating traumatic injuries however, it is hardly imaginable that one can subject human to the adverse conditions for studying the limits the body can tolerate, or assessing if the new protective device will be able to provide adequate protection. In a way, there is a ‘catch twenty two’ situation: in order to prove that safety device is providing adequate protection one should experimentally test it, but without proving it safe experiments with human subjects
Advances in 3D Printing

are impossible. Advanced models allow bypassing many of described restrictions, but along with the benefits, they bring in certain issues of their own, and it is worth looking deeper into these.

Virtual experiments, aka simulations using advanced computer models have obvious strong points. Computer models do not endanger any human test subject; can cover both static and dynamic situations; provide certain power of prediction and are very useful for research and development as well as for studying and teaching. They allow for analyzing “what if” and “ideal” cases, separating parameters “inseparable” in reality, “speeding up” or “slowing down” time and doing other useful tricks, which is not possible with real experiments. Together with advanced means of visualization provided by modern computer technology such models become quite powerful tools in research, development and teaching. However, as with any models, there are certain inherent approximations and limitations of the scope built in them. As for the adequacy of the used model, it should be proven in order to trust its predictions. However, it cannot be done from within the model itself, which is also one of the modeling fundamentals. For proving the adequacy of the model, its predictions should be compared with the results of previous or specially conducted experiments. It should be stressed here, that adequacy of the model is undoubtedly proven only for the tested cases, and is relative (or more correctly, statistically validated for the number of cases tested).

Mathematical and computer (numerical) models also have additional issues and potential for errors related to the limitations in algorithm stability and value quantization. Here numerically stable algorithm means that it does not magnify small errors, e.g. that small and diminishing deviation in the input parameter in turn causes steadily diminishing deviation in the computed results. Strictly speaking, each numerical algorithm should be tested, and the limits for the input parameters that guarantee stability is defined. This is a special task, and with many modeling software packages, the user commonly relies that developers have performed such tasks. Additionally, many of the commercial software packages used for modeling have at least some proprietary modules that are ‘black boxes’ from the user point of view. Therefore, the user may be not aware of additional limitations that were obvious for the model developers.

Yet in addition, mathematical and computer (numerical) modeling demands exact values of the input parameters, some of which can be hard or impossible to extract experimentally, especially when it concerns human body and tissues, forcing the user to ‘synthesize’ some of the input values. Although researchers will use ‘realistic’ values for such synthesized parameters, these can be differing from real ones, and it is not trivial to predict how such differences will affect the simulation results.

Experimenting with human body part surrogates (surrogate twins), or physical modeling, can complement mathematical and computer modeling also helping to cross-validate both approaches as well as underlying concepts. With additively manufactured surrogates, computer and physical modeling can use exactly same 3D shape representation of the body parts. Physical models are using synthetic materials, and necessary properties of these either are known or can be experimentally measured with adequate precision. Thus, computer models can be using exactly same parameters and same settings for the ‘virtual experiments’ that are used for materials and conditions of real experiments carried out using physical models (body part surrogates), simplifying result comparison.

A number of different sensors can be embedded into the body part surrogates, allowing data collection during the experiments carried out in the conditions
mimicking real cases. One can conclude that most productive is the coordinated development of both types of the models allowing for improvements in both of them and increasing the fidelity of their predictions, as schematically illustrated in Figure 1.

One of the specific advantages of physical modeling is in the ability of providing objective information in the cases when the data may carry subjective contributions. For example, individual differences and complications in reproducing exact test conditions have significant impact when human subjects and outdoor tests are concerned. In the cases when one needs to assess the functioning of the garments, footwear and sports, protection or wearable equipment special care is taken to separate contributions of the subjective and objective factors. In such cases, objectivization of the measurements can be a primary target of applying physical modeling even in the situations, when real experiments do not incur any risks for the test subjects and are just inconvenient or uncomfortable.

4. Additive manufacturing of body part surrogates for physical modeling

Modern additive manufacturing in a way can be regarded as a link between the ‘digital world of virtual objects’ and real world with real objects. Indeed, AM technology is a representative of the ‘digitally empowered’ way of modern design and manufacturing providing unprecedented flexibility in the object shapes and allowing for many different materials [17–20]. Files encoding the shape representations of the parts are commonly used for finite element modeling and simulating key properties of the future components. Modern software is already fit to have special inter-platform file formats also used in additive manufacturing. In relation to the biomedicine, it is used for the advanced design of the implants allowing for the case- and patient-specific fitting and implant shape optimization for the chosen functionality [9, 21–25]. Corresponding methods of human body scanning developed for biomedical applications, including optical methods, X-ray computed tomography
Advances in 3D Printing

(CT) and magnetic resonance imaging (MRI) capable of providing high precision spatial information are successfully utilized for constructing high fidelity 3D body part representation for finite element simulations and additive manufacturing of the surrogates replicating real body parts. Additive manufacturing of body part surrogates successfully exploits known advantages of the AM method such as:

- extreme flexibility of the produced 3D shapes;
- easy linking to body part dimensions using files from 3D medical imaging;
- ability to work with different materials; possibility of combining ‘direct’ and ‘indirect printing’;
- cost-effective manufacturing of unique parts and small series;
- easy and well-controlled modification of the existing design;
- easy sharing of the production files with the manufacturers localized in any part of the world.

Here ‘direct printing’ means that the additive machines can directly use corresponding material. In cases, where such material cannot be accepted by the machines or does not provide adequate spatial resolution in AM, one can print the mold from hard material and cast the desired material (which is a common case for soft polymers and gels, and this is often referred to as ‘indirect’ or ‘negative’ printing).

Examples of the particular applications of using additive manufacturing for making body part surrogates using both ‘direct’ and ‘indirect’ printing are given below.

4.1 AM polymer bone and tissue surrogates

Additive manufacturing of human bone and soft tissue replicas is one of the earliest applications for the physical modeling of the human body parts [9–13, 21–28]. Historically, such surrogates were primarily targeting replicating exact 3D-shapes of the selected objects and have found multiple applications as ‘phantoms’ used for the calibration and fine tuning of different imaging devices, and as ‘bone replicas’ used in preoperational planning (see, for example, [29–31]). Preoperational planning using polymer replicas of the fractured or damaged bones today is appreciated by practitioners, often preferring solid 3D models to computer images. Such replicas also allow to perform ‘training runs’ using surrogates aligning and fixing bone fragments of complicated fractures, applying fixation elements and placing screws, all of it without extra stress to the surgeons and any risk to the patient. As a result such ‘pre-operations’ allow decreasing the time patient spends under anesthetics, minimizing post-operational complications and reducing recovery times.

It was also realized, that polymer replicas of the human body parts made using additive manufacturing and basing on the real case 3D reconstructions is a powerful supplement for the teaching [32–34]. Initially these were used mainly for teaching anatomy, but recently such surrogates are used as the mean of teaching practical skills for surgeons. Indeed, bone replicas additively manufactured from acrylonitrile butadiene styrene (ABS, very common polymer used in AM) are not only looking like bones (color, shape), but also the efforts needed to insert the screws into them
quite well replicate that needed in real life cases. Hence, additive manufacturing of bone surrogates allows for compiling collections providing bone replicas for ‘standard cases’ reflecting corresponding clinical cases for the most realistic practical student training. Files used for manufacturing such replicas can be easily shared, and bone surrogates can be manufactured following real demand.

Digital nature of the shape files used for AM allows linking shape modeling to functionality modeling and optimization through finite element simulation adding the value to the pre-operational models of the defect bones. Modern software also allows for complex manipulating of the bone shape files ‘mending the bone models in virtual space’, generating shape-optimized implants and fixation plates, and providing functional optimization of case- and patient specific implants and special surgery tooling (e.g. [35–37]). As a result, clinicians get a full kit including bone replicas, functionally optimized implants and special surgical tools (for example, templates for precision cutting and screw positioning) together with bone surrogates for full scale preoperative planning and training.

An interesting extension of the AM bone surrogate application is recently developed, combining finite element modeling and physical modeling [38–40]. It was realized that spatial fidelity additively manufactured bone replicas based on the CT or MRI scans of a human subject is very high, and that mechanical properties of some polymers are similar to that of natural bone. Hence, it is not only possible to predict bone fracture modalities using finite element analysis, but also possible to perform experiments with monitoring the behavior and fracturing of the bone surrogates under real loading conditions. This case also provides a good example of needed cross-validation of the computer and physical models through the comparison of the predicted and experimentally acquired results.

4.2 AM body part surrogates for studying garment and footwear performance

Assessment of the garment and footwear performance and comfort is quite a complicated task. One can design a test protocol, select a group of human subjects, provide them with apparels to be tested, and send them out for the outdoor testing. After that, subjects fill in special questioners and corresponding answers are analyzed in order to draw conclusions. In many situations like this, it is quite hard to exclude subjective elements from the final assessment. Different wearable sensors acquiring data are often used to make assessment more objective. However, the variations in weather conditions during and between different test sessions can mask the trends and affect the assessment. Moving the tests indoors even when using climate chambers and climate controlled aerodynamic tubes although improve the reproducibility of test conditions still cannot completely remove the subjective components related to human subjects. This substantially affects the ability of objective comparison of the performance and comfort of different garment and footwear designs and models, including the ones coming from different manufacturers.

Full size mannequins are quite helpful for objective assessment of the apparel performance at different conditions including different outer temperatures and even providing ‘perspiration’ and body heat equivalents (see, for example, [41–45]). Such complex setups are unique and not easily affordable. However, in many cases one can use body part surrogates, such as the ones of hand and foot for assessing the performance of the gloves and footwear. Additionally, it is quite possible to include good possibilities for objectively comparing apparels and wearable devices designed for example, for able-bodied or disabled subjects, male, female, children, as well as
the ones reflecting individual body part variability. In such case, a single ‘unified’ computer-based shape model can be properly scaled and easily modified for particular situation. Corresponding surrogates will be additively manufactured with a high spatial precision.

It should be noted, that application of body part surrogates carries very high potential in supporting people with disabilities. Levels of such surrogate complexity can range from simple body part shape models (used, for example, for testing prosthetic sockets and support elements), to the advanced surrogates testing the comfort of different garments, footwear and wearable devices (taking into account distortions in body thermoregulation caused by injuries or amputations).

Described approach can be exemplified by the applications of additively manufactured body part surrogates for assessing gloves and boots for cold conditions Thin-walled shell is additively manufactured in a shape of the hand (foot). Authors use the shape files acquired using optical scans from volunteers. Initial tests were performed using polymer material (ABS), but following tests will be performed using metallic shells (Ti-6Al-4 V, one of the most common titanium alloys manufactured additively). Figure 2 provides a typical example of such surrogate arm shell.

A number of small temperature sensors is embedded into the shell. The sell is filled with water at 32 to 34°C (temperatures of the body extremities are commonly some lower than that of the body core; see for example [44, 45]). Tested glove is placed over the surrogate, or boot (shoe) is placed over the surrogate ‘wearing’ a sock (socks). Assembly is placed into the fridge or freezer (controlled temperature is mimicking desired outdoor conditions) and dynamic temperature reduction at different surrogate positions is recorded. Evaluation of a separate item (glove or footwear) is rather qualitative; it clearly indicates the places where the heat is lost most effectively, and giving an indication how fast does it happen. However, this method easily allows for some quantitative comparison of the gloves and boots (shoes) of different models and different design. In present state this method is already used for supporting the manufacturers in improving heat retaining properties of their products, and comparing their models with the ones supposed to be ‘best in test’.

Figure 2.
Example of a ‘hand surrogate’ shell additively manufactured in ABS for the heat loss assessment of the gloves.
Further developments of the method are under the way. This will need coupling of the physical models to the computer ones; making surrogates better representing thermal properties of the skin and tissue; and adding thin film heaters to represent the heat generated by the body. The issue of materials properly representing the properties of the body tissues is quite complicated and needs special research. Some of the aspects related to matching the properties of synthetic materials are discussed in the following sections.

4.3 Advanced AM body part surrogates with hard and soft tissue

Additive manufacturing is also used for the manufacturing of quite complex body part surrogates combining both hard (bones) and soft (cartilage, tissue, skin) elements. These are ranging from the head and neck surrogates [10–13, 21, 22, 25, 46–50] to some simpler human thigh [51], foot [52], foot and ankle [53, 54] and wrist ones [55–57].

It should be noted, that in accordance with previously stated purpose-centered design of models, known head and neck surrogates are quite different in design and construction. Although all of them are intended to study the dynamic processes happening under the potentially traumatic conditions in the human head, some of them are targeting falls or collisions [10–13, 21, 22, 25, 46, 47], and some—blast injury conditions [48, 49]. The common automotive test dummies de facto also have head and neck surrogates of specific design. However, these are intended for studying impacts with much higher energy, as compared to the cases when head surrogates are used for assessing the falls and a level of protection of different helmets. Commonly car crash dummies have much stiffer neck surrogates, and solid head surrogates with a single sensor set placed in its center of gravity (see, for example, [58, 59]). Indeed, with such impact energy detailed head surrogates with higher biofidelity most probably are not needed.

Although initial tests with the head surrogate developed by the authors together with colleagues, were using Hybrid III crash dummy neck [10–13], after analyzing the data it was concluded that a dedicated neck surrogate should be constructed for better representing the human neck properties. Latest head-neck surrogate developed by
Mid Sweden University and University of Padua is more biofidelic, and the analysis of the data acquired in the corresponding experiments will be published soon.

Figure 3 presents overall view of the head surrogate together with the Hybrid III neck and ski helmet on prepared for the assessment of the pendulum impact (a), separate view of Hybrid III neck with the connection flanges (b), and the overall view of the new biofidelic neck surrogate undergoing compression tests (c). Dimensions and properties of the corresponding body part surrogates are chosen to be as close to that of real ones as possible. Cranium skin and brain models are developed using a CT scan of a volunteer in order to provide realistic dimensions and fit commercial helmets. Brain surrogate weight is chosen close to the statistically average of 1300 g of a human brain accepted in modern anthropology. Hybrid III neck (Figure 3a) is a commercial one, a part of the standard Hybrid III 50th Male crash dummy set by Humanetics.

Human head and neck surrogates developed to the date by the authors and colleagues are designed for studying dynamic processes happening in the human head subjected to the impact of heavy object (in particular case-heavy pendulum), and to assess the protective properties of different helmets. Head surrogates consist of the cranium additively manufactured from ABS; soft rubber brain surrogate with soft fabric mimicking dura matter over it; low viscosity liquid mimicking cerebral fluid; and rubber skin and head tissue surrogate. To provide needed biofidelity, 3D shapes of all components are based upon the processed CT scan of a real subject. Rubber of needed consistence (hardness) today cannot be additively manufactured, so ABS casting forms are prepared for the brain, outer skin and head tissue surrogates, and two-component silicone rubber is molded into them.

A number of sensors is embedded into the system. Three-axis accelerometers and gyroscopes are embedded at different locations of the brain surrogate. To achieve this casting of the ‘brain’ is carried out in steps, embedding sensors at certain level, and casting another layer of the rubber over it. During the tests, additional accelerometers and gyroscopes are attached over the cranium, over the skin surface, on the helmet and on the neck surrogate. Head-neck surrogate is placed over the force platform recording dynamic forces and torques at the base of assembly during and after the impact. Analysis of the signals from the accelerometers and gyroscopes allows for the assessment of the relative motion of the ‘brain’, ‘cranium’ ‘helmet’ and ‘neck’ during and after the impact. A number of the sensors monitoring the cranial fluid pressure is embedded into the ‘scull’ adding to the understanding of interactions between the surrogate elements. Novel sensor allowing measuring the tri-axial compression and strain in the ‘brain’ was developed and embedded into the latest version of the head surrogate [60]. Sampling of the signals during the tests is fast enough to adequately represent the dynamics of the studied processes (3–10 thousand samples of all measured values per second). A number of ski safety helmets including the ones with novel design were assessed using the setup with the described head-neck surrogate. Along with the large amount of data used for the cross-validation of the system, certain mechanisms related to traumatic brain injuries were also clarified.

There is a large number of particular mechanisms leading to human head trauma commonly summarized by the term ‘concussion’. One of the large problems for treating such cases is that the events leading to it are very fast, and often either the patient or surrounding people have no clear recollection about the particular things leading to the trauma. Consequently, doctors can only back-reconstruct possible details (type of impact, direction of the forces etc.) basing on the consequences, which in many cases may show up days after the event. Using experiments with the head and neck
surrogates of the described type mechanisms of some particular consequences can be clarified. For example, appearance of the hemorrhaging at the back of the scull resulting from some frontal head impacts was initially puzzling for us as researchers. Experimental data indicate that with the frontal impacts of certain energy and duration, compression of the cranial fluid at the frontal part of the head causes brain moving back without impacting the frontal part of the cranium. However, at the later stages, inertia of the brain motion causes its contact with the back of the cranium, which starts its return motion supported by the flexion of the neck. Another effect that can be clearly observed with the impact point offset from the vertical symmetry plane of the head-neck system is the cerebellum rotating around its ‘neck’, and two brain lobes moving separately in relation to each other. Such motion can be expected mainly from the rotation of the head, and non-central impact results in both translational motion and strong enough rotational component. In real life event, such impacts can lead to the damage of the axons in the areas where the brain tissue is twisted and is subjected to shear forces. Detailed information about the construction, data analysis and conclusions from the head and neck surrogate experiments can be found elsewhere [10–13, 21, 22, 25, 46–50].

5. Approximations inherent to the additively manufactured body part surrogates

As mentioned in the discussion on general modeling concepts, all models are approximate to some or another degree. Such approximations should be analyzed clarifying possible sources of misrepresentation and errors, and providing the ways for improving fidelity of the body part surrogates as physical models. It is quite clear that two main approximations are coming from the representation of 3D shapes of body parts, and representation of the natural tissues by synthetic materials. It is also worth analyzing what kind of uncertainties is added due to the different aspects of sensors and measurement systems used together with body part surrogates.

5.1 Shape approximations

Although the CT scans or MRI images have high spatial resolution, defining the exact boundaries for the ‘selected body parts’ is not a trivial exercise. Soft tissues often have properties gradually changing even across the body parts regarded by medicine as anatomically ‘well-defined’. Although bone properties are commonly quite different from that of soft(er) tissues, in some cases osteoporotic bones are hard to correctly outline in the X-ray images or in the scan files. Consequently, 3D shape model files resulting from either automated or manual deconvolution based on the image density are already approximate. However, these shape files commonly contain excessive amount of details complicating the situation for the computer modeling software, and in some cases for the software generating the slice-definition files accepted by the production systems using layer-by-layer additive manufacturing. Although additive manufacturing systems in many cases can handle large files with scores of small details in 3D-shape files, finite element modeling and other simulating software either would need too much computing time, or simply would completely reject such files. As a result, 3D shape files are smoothed to be acceptable for both physical and mathematical modeling. For example, in the case of described head-neck surrogate, the ‘wrinkled’ surface of the brain, and both inner and outer surfaces of the cranium
were approximated by the smooth envelopes. Figure 4 presents the images of the smoothed 3D representations of the skull (a) and brain (b), and a photograph of the brain surrogate prepared by casting using molds additively manufactured basing on the smoothed brain shape file.

5.2 Approximations related to synthetic material properties

Another source of approximation relates to the fact that mechanical properties of the synthetic materials do not exactly replicate the ones of natural body tissues. This brings in a number of approximating steps. For example, ABS polymer is not as strong as natural cranium bone and has lower hardness, consequently the temporal sides of the cranium surrogate were made some thicker to provide adequate strength. Although this approximates directly relates to the difference in material properties (human Vs synthetic ‘materials’), it further contributes to the shape approximations. In addition, properties in different parts of the tissue (for example, brain or skin) vary depending on the exact location (see, for example [61]), can be different from subject to subject, or even change for the same subject depending on the level of tissue hydration etc. At present majority of the body part surrogates use different materials only for the tissues with significant differences in the tissue properties (bone, brain, skin and head tissue) and disregard the property variations using same synthetic material in defined sections. In relation to the discussed head and neck surrogate, cranial bone is modeled by ABS polymer, brain- by soft two-component silicone rubber, skin and head tissue- by the two-component silicone rubber harder than that of the brain disregarding any porosity and density variations of natural tissues.

Even bigger source of approximations is due to selecting synthetic materials with properties adequately replicating the ones of natural tissues. As it was mentioned earlier, in order to increase the fidelity of the models and adequate cross-validation, both models should be based on materials with identical properties. However, using synthetic materials with known properties strongly deflecting from that of the natural tissues is of no use. Thus, a choice of materials with ‘good enough’ properties most closely matching that of natural tissues becomes a separate issue.

Studying mechanical properties of natural tissues in itself is a very complex research subject. There exists a number of publications where corresponding parameter values can be found. However, it is not possible to review all different values reported and considerations of variable conditions under which such values were measured within
present chapter. Interested reader can be referred to some relevant publications, and scores of references given therein (see for example [26, 61–65]). Here we should just point out to some of the aspects related to the measuring of corresponding properties.

First of all, properties of the tissues in vivo and ex vivo are different, as the tissue extracted from the body rapidly degrades even if dehydration or drying is prevented by performing the experiments in the buffer solution (see, for example, [64, 65]). Secondly, in many cases mechanical properties of natural tissues are nonlinear [66], and can differ for static and dynamic conditions. The latter is quite critical for adequate computer modeling, but also means that properties of the soft synthetic materials should be measured both under static and dynamic conditions [60]. Additional issues in referring to the measured properties of natural tissues is the spread of the reported values. Indeed, measuring such properties is quite complicated, and often is performed in differing conditions. In addition, some of the publications do not specify measurement conditions exactly, and using such values results in relatively arbitrary decision, which one should be used.

It is also worth briefly discussing if so-called ballistic gel can be successfully used for the brain surrogates. Indeed, ballistic gel of different types (both gelatin-based [67] and synthetic [68]) is quite widely used in different applications. Referring to the purpose of the modeling, main applications of such materials are within modeling of the penetration of different hard elements (including projectiles) into the human body. Gelatin-based gels are hardly acceptable in the cases where long term use of the surrogates is intended, as they do not have reasonable longevity and will degrade being placed for example into a sealed head surrogate. In addition, validation of ballistic gels as model materials was performed with this specific purpose in mind, and would need additional validation if used for different purposes (e.g. human brain surrogate for the impact tests) as compared to what they were designed for. At the moment main medicine-related applications for such ballistic gels is with variety of ‘phantoms’ used for testing or calibrating different scanning devices (CT, MRI or ultrasonic). Novel synthetic ballistic gels can also be rather expensive. Two-component silicone rubber mainly used for manufacturing artistic masks appeared to be an adequate choice in many cases.

Due to the complexity of the subject under the study, validation of the body surrogate models is carried out not only against the computer ones, but also against the measurements acquired using laboratory animals and human cadavers. Corresponding literature on these is quite abundant, but one should be careful with the parameter values measured in animal experiments. Although it is commonly assumed that pigs and primates are relatively good model subjects (e.g. acquired results are again approximate), access to such experiments is quite restricted. Thus, results acquired win the human cadaver studies in many cases are regarded as a ‘golden standard’. Interested readers can be suggested to start from the papers on cadaver studies authored by Nahum et al. [69, 70] and Hardy et al. [71]. In addition, one can start from the papers on the computer models used in head trauma research and protection development authored by Hardy et al. [72], Kleiven et al. [73–76] and Gilchrist et al. [77, 78]. These papers are authored by the multidisciplinary groups with the specialists in medicine, engineering, physics and computer technology.

5.3 Extra uncertainties added by measurement-related errors

There are certain issues related to the measurements contributing to the approximate nature of the body part surrogate systems. As mentioned earlier, a great
advantage of such systems is the possibility to have multiple embedded sensors of different types. However, application of the sensors and integration of them into the measurement system is a separate task demanding special care.

Basing on the common purposes of the body surrogates as models, most commonly used sensors are for the temperature, acceleration (linear and angular), pressure and tension. For the first three types of measurements, one can use modern chip-like components having very small volume (down to 1 mm thick, and few mm footprint, making them almost noninvasive. Pressure sensors are almost equally small, and when used for monitoring cranium liquid dynamics embedding them into the ‘bone’ does not disturb the system. Tension in the bone surrogates can be successfully monitored by the strain gauges. However, the issue of measuring of the tension in soft tissue is not trivial. Strain gauges are very sensitive to bending, their application in soft tissues was tested using silicone rubber samples and disregarded. There are some suggestions that optical fibers can be used for such measurements (e.g. [79]), but so far no body surrogate-based systems using them were reported.

Many modern pressure sensors can detect both positive and negative values, which allows using them inside the soft tissue surrogates to monitor both compression and tension. However, if one needs to make corresponding ‘triaxial’ element, P-sensor tripod is constructed [60]. It is some larger than any of the previously discussed sensors, and its distortion of the soft media should be carefully considered, and resulting sensor element should be carefully calibrated.

Next issue is related to the cables connecting sensors to the measurement system. Each of the sensors needs up to 6–8 connecting wires, and using commercial cabling is too disturbing when embedded into soft tissue surrogates. Authors were forced to make own wire bundles containing enameled wires with outer diameter of 0.10–0.15 mm. These bundles were deformed near the sensors (the part which is resides in the tissue surrogate surrogate) to produce a meander section, which does not prevent free compression-expansion of the tissue surrogate material. Unfortunately, this does not prevent such wires to be broken, and first head surrogate versions were replaced as many of the connections to the embedded sensors were lost. Corresponding bundles of connecting wires coming out of the head and brain surrogates can be seen in the images of Figures 3a and 4c.

Additional issues are related to the sensors, their calibration and ways of data acquisition. In the described head and neck surrogate authors are using triaxial MEMS (micro electromechanical sensors) accelerometers and gyroscopes with large dynamic range (±200 g in linear and ±3000 °/s in angular acceleration) and very small footprint. The manufacturer does not calibrate such commercial chips, and their sensitivity is commonly declared in the datasheets as ‘typical’ with possible deflections within 5–10%. It is possible to calibrate them, but this needs very special complicated and costly equipment. Consequently, authors have accepted the levels of uncertainty declared in the datasheets, and potential errors in measured values are all the time accounted for.

Described head and neck surrogate design is using all sensors with analogue output. One of the basic reasons is the need to monitor multiple sensors with quite high sampling rate. It is possible to have commercial data acquisition systems with even higher than necessary sampling rate and quite large number of analogue input channels. Therefore, limitation to the time resolution of such measurement systems with analogue-output sensors is limited by the sensing elements. Unfortunately, acceleration and gyroscope MEMS sensors with analogue outputs and adequate sensitivity are not manufactured any longer, forcing the migration to the digital output versions. Such digital-output sensors with serial type interfaces are commercially
available, commonly have less connecting wires and allow using bus-type connection (multiple sensors are connected to the same data lines). However, they do not allow for easy arrangement of the synchronized sampling and high acquisition rates with long connecting cables. In many systems with the body part surrogates, such data collection is adequate. However, when fast acquisition rates and large numbers of sensors are needed digital data interfacing becomes problematic. Consequently, it forces reconsidering whole data acquisition concept for the body part surrogates containing large numbers of embedded sensors. To our knowledge, such systems were not yet constructed, and most probably, they will need intermediate small-size microcontroller-based data collection modules embedded into or directly attached to the body part surrogates. These modules should perform synchronized data collection with high sampling rates and storing data into onboard memory, and acquired data transfer into the mainframe computer after the experiment.

Described head-neck surrogate setup using cable connections between the sensors and data acquisition system. This seriously limits its possibilities to the impacts from the falling weights or pendulum strikes. The same time, validation of the protection helmets (including the standard methods) is commonly using drop tests from significant height (one can be referred to good and not extremely specialized sources such as [80–85]). Cable-based data acquisition in such systems is at least inconvenient, and hardly possible in many cases. Potential way forward for the data collection from head surrogate drop tests is applying wireless digital data links to the data acquisition systems and mainframe computers. Such system can be quite technically demanding in design and construction, but would provide much higher flexibility as compared to the wire-link systems. To be successful, such system should overcome potential issues with digital data link stability, and most probably, it should present some compromise between the desire of having multiple sensor channels and capacity of the data rate transfer. Another possibility can be provided by a ‘hybrid’ data transfer scheme using a single optical fiber link between the head-neck surrogates and data acquisition modules. It would be definitely advantageous for the systems, where the ‘surrogate twin’ is stationary, but considering low cost of the modern optical fibers, it can be used for the drop tests, from time to time replacing the damaged fiber link.

Further developments of the complicated ‘surrogate twin’ systems will definitely need alignment with the developments in the purposes for such modeling, including the development of the new standards for the safety equipment testing (see, for example, [84, 85]).

6. Conclusions

Surrogate-based physical models became a potent addition to the computer modeling allowing mutual cross-validation of both approaches and leading to higher result reliability. In many cases, experimental setups using human body part surrogates aiming for testing safety equipment being more intuitively understandable and in some cases providing faster analysis are better appreciated by the industry.

Although additive manufacturing can be regarded as just an enabling tool, body part surrogate-based modeling using AM starts to form own research and development field with fast penetration from comfort and safety applications into the field of medicine and traumatology. Together with embedded sensors, body part surrogates provide data collection in controlled environment and conditions closely reflecting real life situations.
Although different surrogate-based systems are constructed with different target purposes, all of them have similar advantages:

• performing experiments with ‘surrogate twins’ that approximate real humans without endangering any human subject,

• allowing for monitoring and clarification of the dynamics of the processes inside the ‘body parts’ with the sensors placed in positions not even imagined with alive subjects;

• providing data for the cross-validation and improvement of both themselves as physical models, and computer models and ‘virtual twins’;

• providing the means for testing and assessment of the protection devices before they are allowed for any real life use;

• allowing for the objective comparison of the wearables and wearable devices.

Designing and constructing body part surrogate systems should start from clear understanding of the purpose, which will strongly influence the complexity of the surrogates themselves and measurement systems linked to them. Early analysis of the approximations, which are inevitably ‘built into’ each model, including body part surrogates and the overall setup, will prevent many possible mistakes and help avoiding potential disillusions. Thus, two major approaches in further development of the human body part surrogates can be outlined: research-centered and development-centered. Both approaches are actively developed but have different aims.

Research-centered approach commonly aims at quite complex, flexible setups, allowing studies within a number of differing applications under a wide variety of experimental conditions. Such systems commonly have large number of sensor channels providing fast sampling and resulting in large volumes of static and dynamic data. Running such systems, and performing data analysis with such systems is quite complicated and often time consuming.

Although more testing and analysis commonly needed for the industry can be performed by research systems, they are not optimal for many industry-demanded applications. Corresponding development-centered body part surrogate systems should be focusing at certain applications, allowing for faster data analysis and provide the results in the way common for industrial users. Such systems are also easier to manufacture and are less expensive. Our experience shows, that well-designed application-oriented body part surrogate systems that can be used without involving special research personnel have a good potential of becoming commercial products.

Acknowledgements

Authors are acknowledging the input from Professor Nicola Petrone from Padua University, Italy, for conceiving many of the described ideas and participating in the ‘head-neck’ surrogate project. We also acknowledge the contribution of students from Padua University, who were performing their Master Thesis work at SportsTech research Center, Östersund, Sweden, aligned with this project: Ludovico Riello

Conflict of interest

The authors declare no conflict of interest.

Author details

Andrey Koptyug* and Mikael Bäckström
SportsTech Research Center, Mid Sweden University, Östersund, Sweden

*Address all correspondence to: andrey.koptyug@miun.se

© 2023 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
References


[37] Cronskär M, Rasmussen J, Tinnsten M. Combined finite element and multibody musculoskeletal

[38] Emerson N, Carré M, Reilly G, Offiah A. Geometrically accurate 3D FE models from medical scans created to analyse the causes of sports injuries. Procedia Engineering. 2015;13:422-427


Advances in 3D Printing


Body Part Surrogates for Medicine, Comfort and Safety Applications
DOI: http://dx.doi.org/10.5772/intechopen.110119


[77] Horgan TJ, Gilchrist MD. The creation of three-dimensional finite


