Precision human bone prototypes manufactured by 3D printing for training and experimental studies

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Abstract. The work shows the possibility of using additive technologies using 3D printing to build anatomical structures of a person using data of a computer-tomographic examination allows to create precision models taking into account external and internal structure of a biological object.

1. Introduction
The simulation of traumatological and surgical processes is currently performed by computer-aided design methods, which hold a prominent place in the planning and execution of operative interventions. Three-dimensional computer models enable to carry out a structural graphical analysis of the constitution of organs, to determine the patterns of their structure. The first experiment in this field was the American Visible Human Project launched in 1993 at the Colorado University, the USA. Later on other projects were implemented in different countries, namely: Voxel-Man (1998), Visible Korean Human (2001), Chinese Visible Human (2002), Ukrainian Visible Human Project (2005), etc. Nowadays quite a great number of atlases/ programs are available in the public domain. Many educational medical institutions have implemented complexes which enable to work based on the "medicine without patients" principle, that is, to create virtual operating rooms wherein both anatomy is studied and operations are simulated in the interactive mode.
There are actively used 3D-simulation technologies, in particular, CAD (computer-aided design) and CAM (computer-aided manufacturing). Figure 1 shows a knee bone model with guides and pins of a resection block manufactured for planning and performing the total knee arthroplasty. Figure 2 shows the practical application of this guide.
The finite element method has become widespread for assessing the mechanical properties of the bone tissue [1-6]. Much attention is paid to the study of mechanisms in the bone tissue destruction during the normal life and under extreme loads, in particular, under the exposure to high-speed damaging elements [7]. However, the prediction of bone fractures is complicated by the uncertainty both as regards to mechanical bone properties and loads experienced by different skeleton areas. Furthermore, in reality due to many other factors in certain places of the volume the mechanical bone properties may to a considerable degree differ from average ones, however 3D models are “statistically average” and contain no pathologies whatsoever. In particular, Figure 3 shows an example of a bone joint tomogram.

Different components of the bone tissue have various strength characteristics and diverse destruction mechanisms under dynamic loads: from a brittle to ductile one. A cortical bone is more rigid than a spongy bone, so, it withstands larger stress but less relative deformation before rupture. The spongy bone does not break unless the relative deformation exceeds 75%. The cortical bone is destructed when the relative deformation exceeds 2%. Due to its porous structure the spongy bone has a greater ability to absorb energy. Thus, calculations of the stress-strain state even when using such a highly efficient numerical solution as the finite element method may cause an intolerable error.

Moreover, such predictive models do not correctly assess in some cases any possible consequences for the human body. Furthermore, it is known that the damage probability greatly depends on the choice of shoes both for athletes and in case of striking a mine. That is to say, in [8, 9] test results of the lower leg
models of various systems (HIII (N) THOR-Lx (N) MiL-Lx (N)) in shoes (Figure 4) are compared. The development of the Frangible Surrogate Leg (FSL) model shown in Figure 5 was started by the Australia’s Defense Science and Technology Organization (DSTO) in the early nineties as a part of its Human Surrogate Program but found the restricted use.

![Figure 4. SA surrogate HIII THOR-Lx legs.](image1)

![Figure 5. Bone system prototype used for damage analysis [6].](image2)

It should be noted that 61% of the body surface and more than 60% of all combat wounds fall on the limbs. Herewith as known the head and neck constitute about 12% of the body surface but they account for up to 20% of combat injuries and result in 47% of mortality. In [10, 11] the development of technique and technology for testing ballistic helmets is described and current approaches are presented to assessing the severity of damages in simulation of mine explosive injuries.

2. Practical Aspect
It is seen from literature data and material safety data sheets that based only on the "tensile strength" criterion the selection of a material as a bone tissue analogue for testing is not at all difficult. But in fact, everything is much more complicated, as some other factors such as loading speed, impact strength, hardness etc. also exert a significant impact.

As initial data for carrying out works the database of the human elemental bone system is used which has been created at the Privolzhsky Research Medical University or a new prototype is manufactured using computed tomography findings. Upon the completion of the computer-aided simulation using the "slicer" program a G-code is generated. The G-code is edited, if needed. Bone models are manufactured by 3D printers with two print-heads using plastics of different mechanical characteristics.

Figure 6 shows the test results of the bone analogue prototype. It should be noted that the sample in Figure 6.a has demonstrated the minimum impact strength of 0.095 MJ/m², while during tensile tests this sample (100% filling) had its strength equal to the strength of the material made therefrom.

![Figure 6. Example of the impact induced fracture of the samples.](image3)
It is herein to be noted that the anisotropy of elements manufactured under additive technologies and the part location on the table during 3D printing may crucially affect the experiment outcomes. Table 1 shows the outcomes of experiments in the impact resistance assessment for various design options.

| Sample number | Outside diameter, mm | Inside diameter, mm | Number of layers | Filling degree | Impact strength (MJ/m²) |
|---------------|----------------------|---------------------|------------------|---------------|------------------------|
| 1             | 15                   | 4,5                 | 2                | 20            | 0,141                  |
| 2             | 15                   | 4,5                 | 4                | 20            | 0,160                  |
| 3             | 15                   | 4,5                 | 4                | 50            | 0,225                  |
| 4             | 15                   | 4,5                 | 0                | 100           | 0,025                  |
| 5             | 15                   | 9,5                 | 2                | 50            | 0,069                  |
| 6             | 15                   | 9,5                 | 4                | 25            | 0,119                  |
| 7             | 15                   | 9,5                 | 4                | 50            | 0,175                  |
| 8             | 15                   | 9,5                 | 0                | 100           | 0,095                  |

It is seen that the mechanical characteristics of the samples are substantially different. It enables to carry out different experiment with the same geometry of the bone model taking into account both the patient’s age and diseases.

It should be noted that printing with biodegradable materials such as PLA plastic may exert a significant impact on the result of the storage condition of the part after printing.

3. Conclusions

Calculations performed by the finite element method are undoubtedly quite an important area of development. The reproducibility of the results with reality threat depends on the accuracy of conditions assigned for conducting mathematical simulation and the correctness of the mathematical model as a whole.

A physical experiment using bone models enables to obtain an actual pattern of destruction and in some cases to take into account any factors non-integrated into the mathematical model. Additive 3D printing technology for human anatomical structures using computed tomography findings enable to create precision prototypes taking into account the external and internal structure of a biological object. The creation of a test bench based on additive technologies with due consideration of the structure of the limbs and skull bones will improve the reliability of testing.

Moreover, the use of bone models makes it possible to bring the teaching of students to a new qualitative level, since the practical testing on the model of actions under conditions of the operation will reduce the probability of error.

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