TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 57, Issue III, September, 2014

OPTIMIZING UPPER LIMB PROSTHESIS WEIGHT USING BIOMIMETIC APPROACH

Alexandru IANOŞI-ANDREEVA-DIMITROVA

Abstract: *This paper takes a biomimetic approach on weight reduction; it studies the bird bone inner structure and mimics its truss-like appearance in a prosthetic finger. Similar research in bone reconstruction is presented. It is shown two 3D CAD models: one with a truss and one with a honeycomb inner structure; FEA analysis on these models was performed and the results compared and discussed.*

Key words: *biomimetic, FEA analysis, bone, truss structure, honeycomb structure*

1. INTRODUCTION

One of the challenges of successful robotized upper limb prosthesis rehabilitation is weight reduction. In spite of the fact that miniaturization of electronic devices has made a long way to solve this problem, optimizing the mechanical underlay remains the key for further weight reducing. This might be accomplished either by developing new materials which are lighter and stronger, either by using the existent materials in a new way. This paper shows how bioinspired inner-structure of a bird bone can reduce the overall weight of prosthesis, focusing on the mechanical frame of a finger.

It is surprising that, considering the fact that biomaterials (made out of a limited number of chemical elements like C, N, Ca, etc.) which are usually weak and inferior compared to their synthetic counterpart, biological systems as a whole tend to have good mechanical performance [1]. The bird skeleton is a good example of such a system which is suitable to hold up the whole body during flight and landings. The reason of this performance lies in the inner structure of the bone itself, structure which makes it suitable to bear the mechanical stress.

Analyzing and understanding biological morphologies can give valuable data on solving intricate engineering problems; sure, the solutions are not crude copies of the nature, but careful chosen design strategies. It is the current development of additive manufacturing technologies that open a wide field of possibility in integrating such biological microstructures into mechanical devices in order to benefit from what nature has used for a long time.

2. STATE OF THE ART

2.1 Bone mechanics

The bones are bearing the load and provide the infrastructure for locomotion; its mechanical behavior depends on its structure and on its tissue [2]. The forces that act on a bone lead throughout its structure to a complex distribution of stresses, with either a near-linear (for cortical bone), or non-linear (for trabecular bone) response [2].

Bone content is made up to 75% solid mater, the rest of space being taken by fluids; the most prevalent cells are osteocytes that are contained within lacunae and canaliculi, this structure being shared by all vertebrates [3].

Viewed from materials properties point of view, bones have a tensile strength of 150 MPa, 2% strain to failure, a fracture toughness of 4 MPa/m², and a Young's modulus of 15 GPa, which means a good ability to momentarily store energy in straining; below the yield point, this energy is cyclically stored and released, and above the yield point it absorbs shocks, preventing fracture [4].

2.2 Bird bone

Despite the fact that bird skeleton looks fragile, its skeletal mass/soft tissue mass ratio is similar to those of terrestrial mammals, because bird bones are denser, which makes them stronger (bone stiffness and strength is proportional to density); bones hollow cross-section add rigidity, therefore in flight encountered forces pose for birds no significant problem [5].

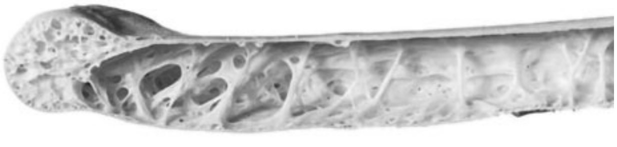

Fig. 1. Red-tailed Hawk (*Buteo jamaicensis*) sagittal section through bone [6]

Both mammals and birds have tubular bones, the key difference being the wall thickness: mammals bone wall is about 25% of total diameter, where birds bone wall can take as low as 5%, with a theoretical minimum of 3.5% [7].

Figure 1 illustrate structural elements, called *trabeculea*, that reinforce the thin walls; it can be noticed how these elements gather closer as it approaches the joint, until they become trabecular (spongy) bone. The main disadvantage is that a structure like this rather breaks than bends.

2.3 Similar research

Similar research is focused on optimizing implantable open-porous scaffold suitable for treatment of bone defects; those open-porous scaffolds are meant to match the mechanical properties of human cortical bone, and are technologically feasible by using additive manufacturing processes. The open-porous structure allows bone ingrowth and, by varying its geometrical shape and size, adjusts its mechanical properties [8]. Figure 2 shows several structures studied in the cited article.

Another approach taken by current research is to obtain the inner structure by fabrication of nanocomposites film and porous scaffold; this method leads to a fibrous, foam-like microstructure characterized by anisotropy, which has an beneficial effect on weight reduction, but, on the other had, deteriorate the mechanical properties [9]. Figure 3 reveal the porous structure as seen by scanning electron microscope (SEM).

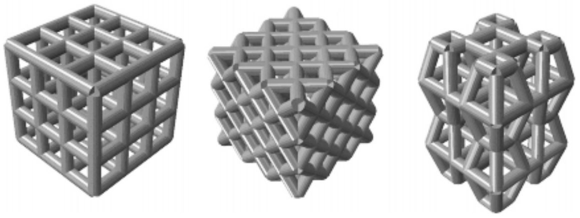

Fig. 2. Various open-porous scaffolds, from left to right: cubic, diagonal and truncated pyramid structure [8]

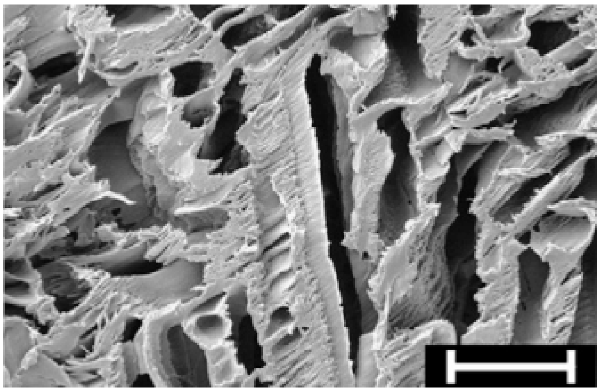

Fig. 3. SEM micrographs of nanocomposites foams [9]

3. CONTRIBUTION

3.1 CAD modeling

In this study a 3D model of an index finger was designed, using the software Autodesk®

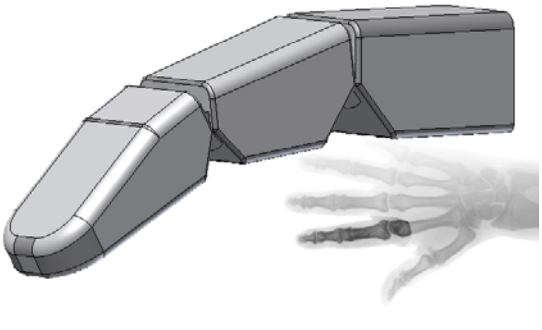

Fig. 4. Finger 3D Model [10]

Inventor®; the model is composed of three individual parts that correspond to the distal, intermediate, and proximal phalanges, joined in an assembly file (figure 4). Both joints flex at maximum 80°, similar to natural joint, where the proximal interphalangeal joints (between first and second phalanx) flex at 100° and the distal interphalangeal joints (between second and third phalanx) at 80° [11]. The outer wall thickness is 0.85 mm.

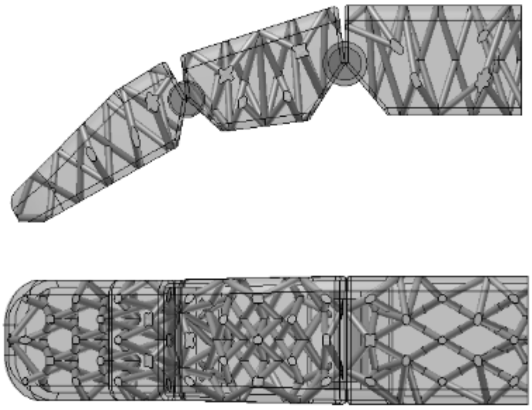

Fig. 5. Truss structure – top and side view

Two inner structures were studied and compared: truss and honeycomb structure. The truss structure was generated by using a 3D sketch as a skeletal model that was filled with struts elements with a diameter of Ø1 mm (see figure 5). The artificial proximal phalange has 76 struts, the intermediate phalange 73 and the distal phalange 65.

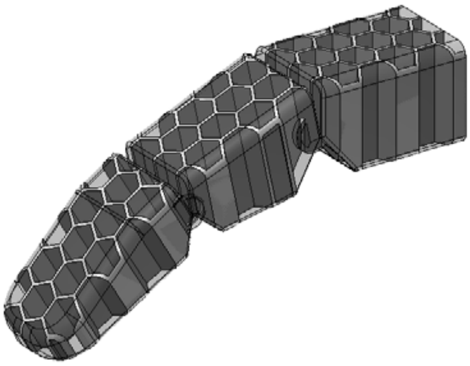

Fig. 6. Honeycomb structure

The honeycomb structure consists of packed hexagonal hollow prism, with an inner wall thickness of 0.5 mm and a flat to flat distance of 5 mm. (figure 6). This kind of structure is known that it used the least material to create a lattice of cell within a given volume, and serves for comparison purposes.

3.2 FEA Analysis

The analysis was performed using the simulation module of Autodesk Inventor®; Acrylonitrile butadiene styrene (ABS) was chosen as the material on which the simulation was carried out, this material being both lightweight and easy to use in a presumptive construction through additive manufacturing.

Two load scenarios were used: the loading of an artificial phalanx under pressure and the loading of the whole structure under a force.

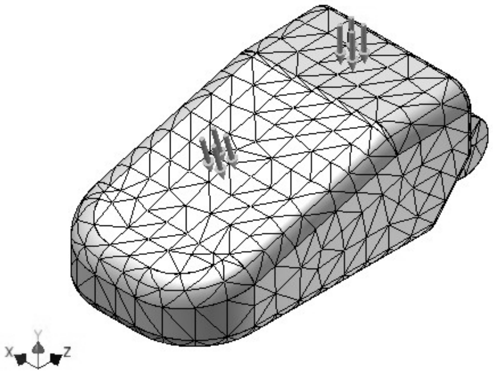

Fig. 7. First load scenario

For the first scenario (figure 7), it was chosen the distal phalanx, because it has a greater risk of being crushed by some kind of object during normal activities. The load was set to 0.5 MPa, which, spread over an area of 310 mm², gives an equivalent force exerted by an 15 kg object under gravitational force.

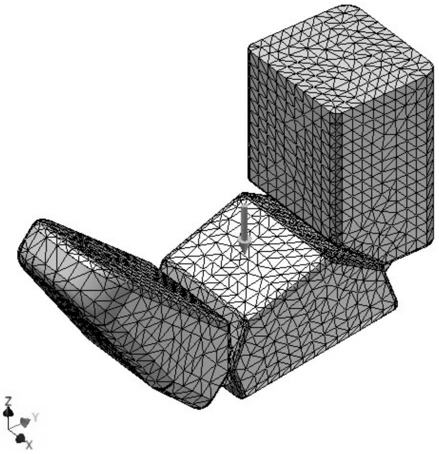

Fig. 8. Second load scenario

In the second scenario (figure 8), the closed finger was put under a load of 20 N; this is slightly less than a natural finger might bear, but enough for daily activities.

4. DISCUSSION

Compared to the honeycomb structure, in the first load scenario the truss structure proved to be slightly inferior in the first case scenario, as seen in table 1; this is expected, as the honeycomb is vertically oriented, being practically under pure compressive load.

Table 1

Comparison between truss and honeycomb structure First load scenario

Criteria	Truss structure	Honeycomb structure
Von Misses Stress [MPa]	27.87	14.27
Maximum displacement [mm]	0.03	0.02
Yield safety factor	1.45	2.83

In the second load scenario (table 2), the truss structure proved to be slightly superior to the honeycomb; it is more elastic under the same load and has a lower equivalent stress, with 27% less material (and consequently weight).

Table 2

Comparison between truss and honeycomb structure Second load scenario

Criteria	Truss structure	Honeycomb structure
Von Misses Stress [MPa]	25.19	30.16
Maximum displacement [mm]	0.98	0.74
Yield safety factor	1.6	1.34

5. REFERENCES

[1] Meyers, M.A., Chen, P-Y, Lin A.Y M., Seki Y. *Biological materials: Structure and mechanical properties*, Elsevier Ltd, ISSN: 0079-6425, Volume 53, Issue 1, 2008

[2] Karim, L, Hussein, A.I., Morgan, E.F., Bouxsein, M.L. *Osteoporosis*, Elsevier Ltd, pp. 431-432, ISBN: 978-0-12-415853-5, 2013

[3] Mishra, S., *Biomechanical aspects of bone microstructure in vertebrates: potential approach to paleontological investigations*, Indian Academy of Sciences, ISSN: 0973-7138, Volume 34, Issue 5, 2009

[4] Taylor, D., *Why are your bones not made of steel?*, http://www.sciencedirect.com/science/article/pii/S1369702110700201

[5] Dumont, E.R., *Bone density and the lightweight skeletons of birds*, http://rspb.royalsocietypublishing.org/content/277/1691/2193.full

[6] Image source: http://www.sciencepartners.info/wp-content/uploads/2012/08/crosssec.jpg

[7] Kaiser, G.W., The inner Bird: Anatomy and Evolution, UBC Press, p. 50, ISBN: 9780774859813, 2010

[8] Wieding, J., Wolf, A., Bader, R., *Numerical optimization of open-porous bone scaffold structures to match elastic properties of human cortical bone*, Elsevier Ltd, ISSN: 1751-6161, Volume 37, 2014

[9] Killeen, D., Frydrych, M., Chen, B., *Porous poly(vinyl alcohol)/sepiolite bone scaffolds: Preparation, structure and mechanical properties*, Elsevier Ltd., Volume 32, Issue 4, ISSN: 0928-4931, 2012

[10] Source of image used in own work: http://techtomove.files.wordpress.com/2013/01/hand3.jpg

[11] http://en.wikipedia.org/wiki/Interphalangeal_articulations_of_hand

Optimizarea greutății protezelor membrului superior printr-o abordare biomimetică.

Această lucrare abordează din punct de vedere biomimetic problema reducerii greutății; este studiată structura internă a oaselor păsărilor, apoi imitată în cazul unui deget protetic. Au fost studiate abordări similare în ceea ce priveşte reconstrucția osoasă. Sunt prezentate două modele 3D CAD: unul cu o structură internă tip grindă cu zăbrele, celălalt cu o structură tip fagure de miere; acestea au fost analizate prin metoda analizei cu element finit, iar rezultatele au fost comparate.

Alexandru IANOŞI-ANDREEVA-DIMITROVA, M.Sc. Student, "Petru Maior" University of Tg. Mureş, Faculty of Engineering, ianosi.alex89@yahoo.com, Nicolae Iorga 1, Tg. Mureş, Romania.