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First attempts to 3D printing spine implants – human spine biomechanics

The purpose of this paper was to obtain and compare information about spine metrics properties and indicate of polymer materials for the manufacture of spinal implants using 3D printing. The resulting properties will allow to select the material which have similar spine metrics properties or better. The literature review will be helpful to develop methodology of 3D printing in producing implants of the vertebrae and intervertebral discs (VaI). The project consists three main phases: creation a creation model which is based on generating of a 3D model (VaI) discs of tomographic images spine using software specially developed for medical image processing and CAD software (VaI) discs, creation of a prototype implant and performance strength tests on the obtained implant.

Keywords: *spine, vertebra, metric properties, mechanical properties, implant*

1. INTRODUCTION

Body support, musculoskeletal system, and finally, a protection of the spinal cord – these are spine's basic tasks in human body [1]. Continuous development and progress of civilization cause the increase in the amount of spine injuries and its deformation (defect attitude). Only the right exploitation and appropriate medical support can guarantee the best fulfilment of these functions for as long as possible. Biomechanics and appropriate material knowledge as a science from the border of medicine and technology deals with locomotion (its causes and consequences), and testes mechanical properties of tissues, organs and systems, is essential for the characteristics of function and spine's mechanical properties. Exploring structures and phenomena occurring in the spine during the exploitation in lifetime, it a necessary condition for constructing (and the following – producing) implants and medical devices whose purpose is to support the realization of the spine specific functions. This article is dedicated to a review of the widely available literature dealing with the issues of the structure and properties of the human spine as a background for preparing 3D printed implant model. Cervical segment is the most frequently damaged as a result of traffic collisions.

2. SPINE VERTEBRA INTERVERBAL DISCS ANATOMY

The spine is one of the most important elements of the skeletal system in vertebrates. In the human body it protects the spinal cord enables movement and support to the organism [1]. The column consists of 33–34 vertebrae arranged one above the other, which are interconnected by the soft tissue such as the intervertebral discs, ligaments and muscles [1, 2].

The spine is divided into five sections. Cervical consists of seven vertebrae and a head support. The characteristic vertebrae of cervical section are the two first vertebrae, atlas which does not have a shank, the spinous process and its shape is annular. The second characteristic vertebra is axis, it has extended core to up which ends with dens. The cervical vertebrae are the smallest of the true vertebrae of the spine [2, 3]. Below, there are twelve thoracic vertebrae, which are connected movably to the ribs and sternum. They have a smaller vertebral foramen than the spinal vertebrae and less mobility than cervical and lumbar. The lumbar section consists of five vertebrae that have bigger bodies. Next five circles consist of sacrum section, which fuse with age. The last section of the spine is part of the coccyx, which is made up of four to five vertebrae, which, like in the sacral section are fusing [2, 4]. Vertebrae is composed of spinous process, which is the front part of a vertebra, and the arc of the rear part of vertebra which is permanently connected to the vertebral body. Arch along the rear surface of vertebral body forms a vertebral foramen [1, 2]. Vertebra in the middle consists of a core with a sponge, which is surrounded by the cortical tissue layer, while at the top and bottom of the circle are incremental plates, which are composed of cortical tissue. There are 23 intervertebral discs in the spine, which connect two shaft surface adjacent vertebrae. The purpose of the intervertebral disc ensuring the stability of the spine, damping the vibrations transmitted through the spine to the head, and being the link that allows the movement of the adjacent vertebras. To a large extent, functions performed by the intervertebral discs depend on their saturation by water and the degree of degeneration [2]. The average length of the spine adult male is 70–75 cm. The length of the spine is based on the addition of bodies height and intervertebral discs compared to ¾ vertebrae ¼ vertebral discs. Effect on the mechanical strength of the spine has a density which is measured by densitometry test. For women aged 65 the correct density is 0.963 ± 0.153 [5].

3. MECHANICAL PROPERTIES OF BONE STRUCTURES HUMAN SPINE MATERIAL

According to the theory proclaimed by the Mayer, Culman and Wolff in the second half of the XIX century, bone's internal structure depends on distribution of stresses and strains. Wolff's law, which was created basing on the mentioned thesis proclaims: bone's trabeculae structure adapts under equilibrium conditions to the direction of principal stresses. This means that bone's load changes resulting in lack of overlap axis direction of principal stresses and anisotropic axis (trabeculae), cause the adjustment of the bone's structure to the current state of stress [1, 6, 7]. Theory of internal transformations presupposes that bone's tissue density changes with stress – the increase of the bone load causes the increase of the density [1, 8]. This theory and specific bone structure have an influence on the bone's mechanical properties, which is based on the two pillars: fundamentals of theoretical physics and experiences regarding the characteristics of the material of concerned substance [1, 2].

Value of the vertebra's and intervertebral disc's mechanical properties described by Yamada for tension, compression and torsion test carried out by Sonoda. The above-mentioned study carried out on the sectional preparations taken from corpses of adults (20–70 years), which were divided according to the age within given spine's segment: cervical, upper thoracic (Th1 – Th4), middle thoracic (Th5 – Th8), lower thoracic (Th9-Th12), and lumbar segments (Table 1). Described tests include the identification:

- bone's structures (vertebrae's) strength during:
    - ○ tension test along the longitudinal axis of the spine (7 spines),
    - ○ compression test, in which direction of the compressive force coincides with the axis of the spine (22 spines),
    - ○ torsion test, in which torque's (moment) vector coincides with the longitudinal axis of the spine (11 spines),

- intervertebral disc's strength during:
  - ○ tension test along the longitudinal axis of the spine (7 intervertebral discs),
  - ○ compression test, in which direction of the compressive force coincides with the axis of the intervertebral discs (for preparations derived from the corpses of people aged from 40 to 59 years),
  - ○ torsion test, in which torque's (moment) vector coincides with the axis of the intervertebral dicsc (11 preparations).

Bone structure is characterized by:

- the greatest compressive strength – average values are in the range from 4.7 MPa (for lumbar segment) to 10.3 MPa (for cervical segment),
- comparable tensile and torsion strength for all segments – average values are in the range 2.9 – 3.8 MPa,
- higher strength for preparations of patients with age range from 20 to 39 years,
- the greatest tensile and compressive strength of the cervical segment, and the greatest torsion strength of the thoracic segment (no data on cervical segment).

Intervertebral discs can be characterized also by:

- the greatest compressive strength, minimum tensile strength,
- higher strength for preparations of patients with age range from 20 to 39 years,
- the highest strength: tension in cervical segment, compression in lumbar segment, and comparable values of torsional strength values for cervical and lumbar segment.

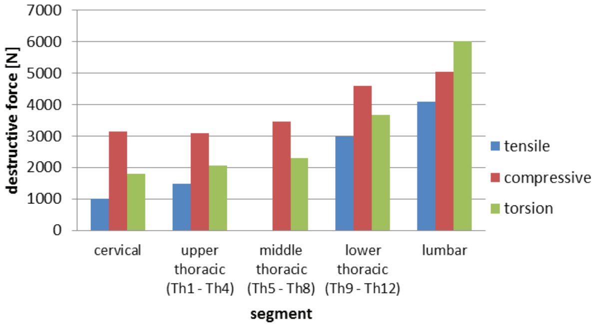

Fig 1. Destructive forces for spine segments [1]

Comparison of the value reported in the literature destructive forces for: cervical, upper thoracic (Th1 – Th4), middle thoracic (Th5 – Th8), lower thoracic (Th9 – Th12), and lumbar segments (Fig. 1) [9, 10, 11, 12, 13].

Table 1. The average values of spine strength [1, 9]

		Strength[MPa]		
	Segment	Tensile	Compressive	Torsion
Vertebrae	Cervical	3.2	10.3	-
	Upper thoracic (Th1 – Th4)	3.4	7.2	3.3
	Middle thoracic (Th5 – Th8)		6.1	3.2
	Lower thoracic (Th9 – Th12)	3.6	5.4	3.1
	Lumbar	3.8	4.7	2.9
Intervertebral discs	Cervical	3	10.8	4.8
	Upper thoracic (Th1 – Th4)	2.1		4.1
	Middle thoracic (Th5 – Th8)			4.4
	Lower thoracic (Th9 – Th12)	2.3		4.5
	Lumbar	2.6		4.8

Analyzed data can be concluded that the highest strength is characterized by lumbar segment's vertebrae and the lowest cervical segment's vertebrae, which has a direct relationship with differences in the construction of these vertebrae's groups. It should be also underlined that the results reported by different authors differ from each other, which highlights the existing problem associated with the lack of standardization of research techniques for biological structures, and differences related to the individual characteristics.

4. THE ETIOLOGY OF SPINAL INJURIES

Based on the described research [14] it can be concluded that the most common causes of spine injuries are pathological injuries (28.5%), traffic collisions (27.7%) and falls from heights (20.0%). As a result, the most frequently damaged segments were: thoracic (34.6%), cervical (32.3%) and lumbar (23.8%) (fig. 2) [14]. Nemcunowicz–Janica A. and collaborators report that 59% of spinal injuries are caused by falls from heights, and 33% by traffic collisions [15]. Fife and collaborators determine the frequency of cervical segment's damage on 61%, thoracic – 16%, and both thoracic and lumbar segments on 19% (Fig. 3) [16].

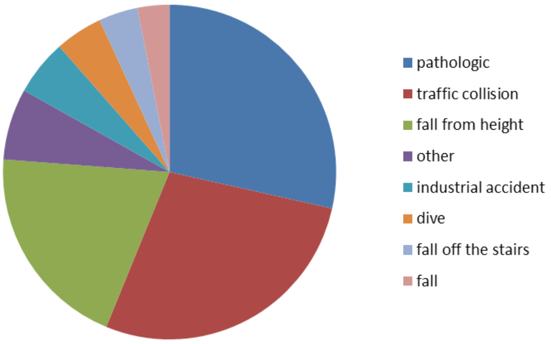

Fig 2. Causes of spine injuries [14]

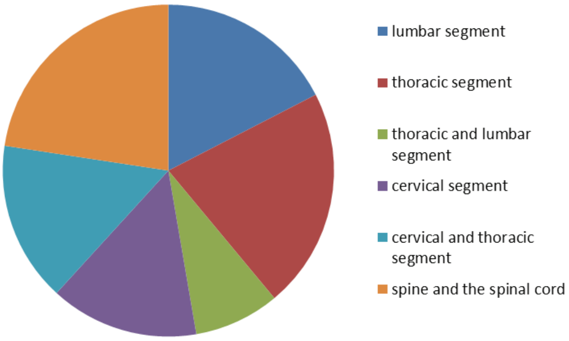

Fig 3. Location of spine injury [%] [14]

5. SPINE ARTIFICIAL IMPLANTS

The spine is an essential organ for the proper functioning of organisms. Although it is protected by a number of tissues, it can be damaged. In order to restore even the partial performance, it is possible to use many surgical techniques, including techniques for of the spine implants.

Large progress in materials science allows to use many types of biomaterials with better and better properties. In spine implantology titanium and its alloys, plastics, are often used. Titanium is non-toxic even in large doses, has no effect on the human body, moreover it has several times lower thermal conductivity than conventional prosthetic materials, high hardness, mechanical strength and durability (Table 2) [17]. Besides, it does not cause allergic reactions and is resistant to corrosion, that is why it has a very good biocompatibility. [18] Titanium is used in the method of posterior lumbar interbody fusion (PLIF). It is one of the treatments spine in which are used vertebral body pivots, often made of titanium and polyether ether ketone (PEEK). [19, 20]. Nitinol (Ni-Ti), due to the shape memory, is a frequently used titanium alloy. Spacer sleeves to the spine are made from the nitinol [21]. Similiar to other titanium alloys nitinol has good mechanical properties and biocompatibility (Table 3).

Table 2 Titanium alloys properties [17]

Alloy	Young's modulus (E) [GPa]	Tensile strength (σ_r) [MPa]	Yield strength Ys 0,2 [MPa]	Fatigue limit FL [MPa]
Ti	105	785	692	430
Ti-6Al-4V	110÷114	960÷970	850÷900	620÷725
Ti-6Al-7Nb	105	1024	921	500÷600
Ti-5Al-2,5Fe	110	1033	914	580
Ti-6Al-4V ELI	101÷110	860÷965	795÷875	598÷816
Ti-13Nb-13Zr	79	1030	900	500

Table 2 Titanium alloys properties [17]

Alloy	Young's modulus (E) [GPa]	Tensile strength (σ_t) [MPa]	Yield strength Ys 0,2 [MPa]	Fatigue limit FL [MPa]
Ti	105	785	692	430
Ti-6Al-4V	110÷114	960÷970	850÷900	620÷725
Ti-6Al-7Nb	105	1024	921	500÷600
Ti-5Al-2,5Fe	110	1033	914	580
Ti-6Al-4V ELI	101÷110	860÷965	795÷875	598÷816
Ti-13Nb-13Zr	79	1030	900	500

Table 3 Nintinol properties

Physical properties	Values
Density [g/cm^3]	6.45÷6.50
Melting point [^{o}C]	1250÷1310
Tensile strength [MPa]	600÷800
Yeld strength [MPa]	400÷600
Elongation [%]	20÷40
Causing deformation of the shape memory effect [%]	6÷8

PEEK is a thermoplastic polymer that is also used in the method of posterior lumbar interbody fusion [19, 20]. It shows very good mechanical properties (Table 4) and good chemical resistance [22].

Table 4 PEEK properties [23]

Physical properties	Values
Density	1.320 g/cm^3
Young's modulus (E)	3.6 GPa
Tensile strength (σ_t)	90-100 MPa
notch test	55 kJ/m^2
Glass temperature	143 °C
melting point	~343 °C
Thermal Conductivity	0.25 W/m.K
Water absorption, 24 hours (ASTM D 570)	- 0.1%

6. BIOMATERIAL DEVELOPING

Selection of the appropriate biomaterial is associated with overcoming some difficulties related to biotolerance, which is considered as an individual feature. The degradation or depolymerization are affected by such factors as the displacement, strain or tissue pH. Biomaterials should have also bioelectrical compatibility feature, whose task is to minimize the negative body reactions such as allergic, carcinogenic, whether toxicological pyrogenic. Another feature of the biomaterial are material properties for safe and reliable operation of the arrangement implant, tissue, body fluid [21].

The polymeric biomaterials for 3D printing should easily to obtain a reproducible quality for different batches of products, easily formed without degradation of the material, ease of sterilization, without any changes in the properties or shape, appropriate quality of physicochemical materials and final products, durability and reliability [21]. Features a polymer require experimental verification and therefore in research will be used rapid prototyping technology. Rapid prototyping is a technique that allows prototype fast creation with previously created a three-dimensional model using CAD software. Obtained model is then printed with previously developed biomaterial using a 3D [24] printer and then subjected to the tests to check whether it has the desired physicochemical properties.

The spine is a complex organ, which plays a very important role in the body so that it can be damaged due to natural accidental causes. For this purpose, specialized studies are conducted to examine the strength of the spine. These tests allow to obtain information which allows design the implant in such way as to used biomaterial have similar or better mechanical properties than the spine. Due to the facts titanium alloys implants are used in lumber section where is high strength need for heavy loads. Nitinol is made for spine sections where is need to use shape memory like spine stabilization for cervical and thoracic segment. PEEK is used in spine sections where is need for shock absorption. According to the literature the difference of spine sections strength arises from difference in the construction of individual vertebrae. Results of strength tests by different authors differ from each other due to the lack of testing techniques standardization for biological structures and differences associated with individual traits. The way to solve results divergence is mathematical modeling, which allows to obtain satisfactory results.

7. LITERATURE

1. Będziński, R. Biomechanika inżynierska : zagadnienia wybrane. Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław, 1997.
2. Gzik, M. Biomechanika kręgosłupa człowieka. Wydawnictwo Politechniki Śląskiej, Gliwice, 2007.
3. Woźniak, W. Anatomia człowieka. Podręcznik dla studentów i lekarzy. Elsevier Urban & Partner, Wrocław, 2010
4. Wójtowicz, Z. Podstawy anatomii człowieka. Czelej, Lublin, 2009
5. Riggs, B. L., Wahner, H. W., Dunn, W. L., Mazess, R. B., Offord, K. P., Melton, L. J. 3rd Differential changes in bone mineral density of the appendicular and axial skeleton with aging: relationship to spinal osteoporosis. *The Journal of Clinical Investigation* 67 (2) 1981: pp.328–335
6. Boyle, C., Kim, I.Y. Three-dimensional micro-level computational study of wolff's law via trabecular bone remodeling in the human proximal femur using design space topology optimization *Journal of Biomechanics* 44 (5) 2010: pp 935–942
7. Chen, J., Liu, C., You, L, Simmons, C. A. Boning up on Wolff's Law: Mechanical regulation of the cells that make and maintain bone *Journal of Biomechanics* 43 (1) 2010: pp. 108–118
8. Błaszczyk, J. W. Biomechanika kliniczna: podręcznik dla studentów medycyny i fizjoterapii. PZWL, Warszawa, 2004
9. Yamada, H. Strenght of biological materials, The Williams and Wilkins Company Baltimore, 1970
10. Teo, E.C., Ng, H.W. First cervical vertebrae (atlas) fracture mechanism studies using finite element method *Journal of Biomechanics* 34 (1) 2001: pp. 155–164
11. Teo, E.C., Paul, J.P., Evans, J.H., Ng, H.W. Experimental investigation of failure load and fracture patterns of C2 (axis) *Journal of Biomechanics* 34 (8) 2001: pp. 1005–1010
12. White, A. A., Panjabi, M.M. Clinical biomechanics of the spine. Lippincott Williams & Wilkins, Philadelphia, 1990
13. Jasiński, R., Pezowicz, C. Experimental investigation of the axis dens fracture *Acta of Bioengineering and Biomechanics* 6 (1) 2004: pp. 51–60
14. Rosińczuk-Tonderys, J., Załuski, R., Gdesz, M., Lisowska, A. Spine and Spinal Cord Injuries – Causes and Complications *Advances in Clinical and Experimental Medicine* 21 (4) 2012: pp. 477–485
15. Niemcunowicz-Janica, A., Janica, J.R., Ptaszyńska-Sarosiek, I. Spinal cord injuries in material of Department of Forensic Medicine in 2001 – 2005 *Archiwum Medycyny Sądowej I Kryminologii* 57 (3) 2007: pp. 298–301
16. Fife, D., Kraus, J. Anatomic location of spinal cord injury *Neurologic Clinics* 9 1991: pp. 625–661.
17. Emsley, J. Nature's Building Blocks: An A-Z Guide to the Elements. Oxford University Press, Oxford, 2001
18. Skocaj, M., Filipic M., Petkovic J., Novak, S. Titanium dioxide in our everyday life; is it safe? *Radiology and Oncology* 45 (4) 2011:pp. 227–247
19. Ciupik, L., Hakało, J., Zarzycki, J. Jednoczesne odbarczenie przestrzeni międzytrzonowej poprzez rotację czopa prostokątnego ze stabilizacją w zmodyfikowanej metodzie R-PLIF
20. Kurtz, S. M., Devine J. N. PEEK Biomaterials in Trauma, Orthopedic, and Spinal Implants *Biomaterials* 28 (32) 2007 :pp. 4845–4869
21. Marciniak, J. Biomateriały. Wydawnictwo Politechniki Śląskiej, Gliwice, 2002
22. Material Properties Data: Polyetheretherketone (PEEK), www.makeitfrom.com [access date: 22.06.2015]
23. Van der Vegt, A.K., Govaert, L.E. Polymeren: van keten tot kunstof. Delft University Press, 1999.
24. Budzik, G., Budzik, W., Cygnar, M., Janisz, K. Możliwości zastosowania szybkiego prototypowania w procesie projektowania i wytwarzania elementów pojazdów samochodowych *Problemy Eksploatacji* 2009: pp. 7–16

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