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Abstract	Personalized orthopedics became possible in pre-clinical and clinical practice primarily through the application of engineering solutions in the prevention, diagnosis, and treatment of orthopedic patients. In order to predict the further development of personalized orthopedics, it is necessary to look at which enabling engineering technologies can be applied and where their impact is expected. This paper identifies and analyzes those technologies.

Keywords (separated by '-')	Personalized Orthopedics - Enabling Technologies - Engineering

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The Impact of Engineering Enabling Technologies on the Further Development of Personalized Orthopedics

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Abstract. Personalized orthopedics became possible in pre-clinical and clinical practice primarily through the application of engineering solutions in the prevention, diagnosis, and treatment of orthopedic patients. In order to predict the further development of personalized orthopedics, it is necessary to look at which enabling engineering technologies can be applied and where their impact is expected. This paper identifies and analyzes those technologies.

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Keywords: Personalized Orthopedics · Enabling Technologies · Engineering

1 Introduction

It has been known for a long time that a personalized approach in medical practice provides the best benefits to patients, but this was not possible due to the lack of sufficiently detailed data on the patient's condition and characteristics, equipment, and techniques for personalized approach. However, the development of many engineering technologies in the last fifty years has resulted in innovative solutions that have also been applied in orthopedics. Thus, step by step, the conditions for a personalized approach in orthopedic practice were created. This tendency has not stopped but is developing faster and faster.

The aim of this study is to identify, based on bibliometric analysis, the main engineering enabling technologies that contribute to the development of personalized orthopedics, to point out their importance, and to briefly present those that have the greatest impact.

2 Bibliometric Analysis

2.1 The Importance of Engineering Technologies for the Development of Orthopedics

There are indications that engineering technologies have significantly influenced the development of orthopedics in the last fifty years. Also, it is considered that they especially enabled a personalized approach in orthopedics [1]. However, it is not clear how much impact engineering technologies have had on orthopedics and which engineering disciplines have had the greatest impact on the development of orthopedics.

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In order to get an answer to this question, a simple bibliographic research was done using Core Collection database of the Clarivate Analytics Web of Science (WoS) platform [2]. Bearing in mind that various terms related to orthopedics are used in the scientific literature, and with the intention of being comprehensive, the following search query was used: Orthopedics OR Orthopedic OR Orthopaedics OR Orthopaedic OR Bones. The "All fields" option was used for the search, which includes title, abstract, author keywords, Keywords Plus (terms automatically generated from the titles of cited articles) and any other metadata available for that article. The search result showed that there are 1,035,427 publications in the Core Collection that contain at least one of the search terms. The search covered the period from 1996 to 2023.

Search terms were found in a total of 254 Web of Science categories. Table 1 shows the first 10 categories sorted in descending order by the number of articles in which the search terms were found. Other categories are not shown to save space. It is obvious that the largest number, a total of 159,817 articles, is in the Orthopedics category, which is 15.435% of total 1,035,427 publication.

Table 1. Top ten Web of Science categories with the largest number of articles that contain the searched terms.

Web of Science Categories	Number of articles	% of 1,035,427
Orthopedics	159817	15.435
Surgery	102888	9.937
Endocrinology Metabolism	77551	7.490
Oncology	74956	7.239
Hematology	69577	6.720
Dentistry Oral Surgery Medicine	57025	5.507
Engineering Biomedical	50034	4.832
Cell Biology	48409	4.675
Medicine Research Experimental	45249	4.370
Immunology	43951	4.245

Among the 254 Web of Science categories in which the searched terms were found, there are also 36 engineering categories. In the Table 2 only first 15 engineering categories are sorted and presented in descending order by the number of articles in which the search terms were found.

The total number of articles from engineering categories is 271,720 or 17.191%. Of course, some of these articles are not necessarily related exclusively to orthopedics, but also to other disciplines, such as surgery, but obviously the influence of engineering disciplines on medicine, and therefore on orthopedics, is huge.

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Table 2. Top fifteen engineering Web of Science categories with the largest number of articles that contain the searched terms.

Web of Science Categories	Number of articles	% of 1,035,427
Engineering Biomedical	50034	4.832
Radiology Nuclear Medicine Medical Imaging	40881	3.948
Materials Science Biomaterials	34123	3.296
Materials Science Multidisciplinary	20622	1.992
Cell Tissue Engineering	19292	1.863
Chemistry Multidisciplinary	12953	1.251
Physics Applied	9868	0.953
Nanoscience Nanotechnology	7543	0.728
Chemistry Physical	6857	0.662
Polymer Science	5903	0.57
Engineering Electrical Electronic	5095	0.492
Materials Science Ceramics	4854	0.469
Metallurgy Metallurgical Engineering	4587	0.443
Physics Condensed Matter	4225	0.408
Engineering Mechanical	3013	0.291

2.2 The Most Influential Enabling Engineering Technologies in the Field of Orthopedics

In order to recognize the most important engineering technologies that contribute to the development of personalized orthopedics, another bibliometric analysis was performed on the WoS platform. This time the following query was used (Orthopedics OR Orthopedic OR Orthopedics OR Orthopedic OR Bones) AND Personalized (Topic). The "Topic" option was used for the search, which includes title, abstract, author keywords, and Keywords Plus.

As a result of the query, 2855 papers containing the requested terms were found. With further refinement, only papers from 2021 to 2023 were selected, and all papers that do not belong to pure orthopedic disciplines were rejected. Thus, the scope of research was reduced to 983 published papers. A statistical analysis of keywords defined by the author was performed for the selected papers. The results of this analysis are presented in Table 3.

Although the analysis done is indicative, it is not perfect. The problem lies in the fact that the granularity of the keywords that the authors mention is different, and different keywords are assigned to the same things. For example, the main keyword in works dealing with the application of titanium alloys for the manufacture of implants is found in the forms: biomaterials, titanium alloy, Ti 6Al 4V, or Ti6Al4V ELI (Grade 23). The same is valid for the case of 3D printing and Additive manufacturing.

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Table 3. Frequency of top ten keywords related to engineering enabling technologies in orthopedics.

Engineering technology	Frequency
Additive manufacturing	26
3D Printing	15
3D bioprinting	8
Finite element analysis	8
Computed tomography	6
Machine learning	6
Computer aided design	6
Tissue engineering	5
Artificial intelligence	7
Biomaterials	7

3 Enabling Engineering Technologies in Orthopedics

3.1 Additive Manufacturing

Additive manufacturing technologies, often referred to as 3D printing, has one of the biggest impacts on the development of personalized orthopedics. The possibility of these technologies to produce efficiently objects of very complex shapes has enabled the production of personalized implants, scaffolds, prostheses, orthoses [3] and surgical tools [4]. Also, these technologies can be used to create models of a patient's bones or
AQ3 joints for planning surgical procedures and thus optimize surgical outcomes (Fig. 1).

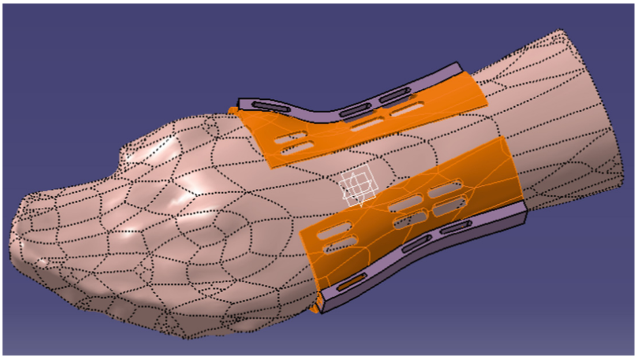

Fig. 1. Personalized orthosis made of Ninja Flex with FDM additive manufacturing technology [3].

Additive manufacturing is a mature technology that, together with new materials, can not only achieve any shape, but also enables the creation of porous structures that,

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in the case of scaffolds, allow better innervation and a larger surface area for cells to adhere and proliferate, which promotes new tissue formation [5]. To further promote the growth of bone tissue within porous implants and scaffolds, surface coatings are used.

One of the new additive manufacturing technologies that is being worked on in many laboratories is bioprinting [6]. It uses 3D printing techniques to create living tissue constructs by layering and depositing cells, growth factors, and biomaterials in a controlled and precise manner. Most of bioprinters are using extrusion as a method for building layers, but other methods, such as stereolithography, inkjet or laser-asisted method. Most of the research involving bioprinters is directed towards the production of bone tissue and cartilage.

Another promising technology is 4D printing, which is additive manufacturing with the added capability of creating objects that can change their shape or properties over time, in response to external stimuli such as temperature, moisture, pressure, or light. This is achieved by using advanced materials, such as shape-memory alloys, smart polymers, or hydrogels, that can be programmed to respond to specific environmental conditions. The use of 4D printing to create implants with predetermined shape and size allows for a precise fit at defect sites. During the post-printing stage, the implant may undergoes functional transformation and mimics biological features, which promotes tissue remodeling and maturation [7].

Additive manufacturing is particularly important for the further development of regenerative medicine. Stem cell therapy and platelet-rich plasma therapy may become more widespread in orthopedics. This could allow for the repair of damaged bone tissue and the regeneration of lost cartilage.

3.2 Biomaterials

Biomaterials are biocompatible materials that are used in medical devices, implants, and tissue engineering to replace or repair damaged or diseased tissues. The most commonly used metal materials are stainless steel (316 L), titanium alloy (Ti6Al4V), and cobalt-chromium alloys (F75 CoCr). They are mainly used for the production of implants, fixation devices, scaffolds and auxiliary instruments. These materials are strong, durable, and resistant to corrosion, making them ideal for use in load-bearing applications such as hip and knee replacements [8].

Ceramics such as alumina (Al2O3), zirconia (ZrO2), and calcium phosphate are also used in orthopedic implants. These materials are biocompatible, meaning they are well-tolerated by the body, and can be shaped and sized to fit individual patients.

Polymers such as polyethylene, polyurethane, Teflon and silicone are commonly used in orthopedic implants, particularly in joint replacements. These materials are lightweight, flexible, and can be easily molded to fit a variety of shapes and sizes.

The emergence of new advanced materials has enabled the production of scaffolds with improved properties. Currently, work is being done on the production and improvement of composite scaffolds that can be metal, ceramic or polymer based. Additive manufacturing is mainly used for the production of composite scaffolds [9].

While autografts are currently considered the best option for orthopedic tissue reconstruction, there is a limit to the amount of tissue that can be harvested without causing

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harm to the donor site. Tissue engineering approaches, which involve using decellularized bone, cartilage, skeletal muscle, tendon, and ligament from allogeneic or xenogeneic sources, have emerged as a promising alternative treatment option. The extracellular matrix, which acts as a natural scaffold for cell attachment, proliferation, and differentiation, plays a vital role in these approaches. Decellularization of in vitro cell-derived matrices can also enable the generation of autologous constructs using tissue-specific or progenitor cells. While decellularized bone tissue is widely used in orthopedic applications, the potential of using decellularized cartilage, skeletal muscle, tendon, and ligament cell-derived matrices is only now beginning to be explored for potential clinical translation in the orthopedic setting.

3.3 Computer Aided Design

Computer aided design (CAD) has many different applications in personalized orthopedics, so it has significantly contributed to its development. The most common application of CAD in orthopedics is for the design of personalized implants, prosthetics, scaffolds, and surgical tools. In order to achieve anatomical personalization, the patient's CT image is usually the starting point.

Second important application of CAD is in surgical planning. Planning surgeries in advance, allows surgeons to better visualize the procedure and optimize the approach. This can lead to more accurate and efficient surgeries with reduced risk of complications. Similar approach can be used for a rehabilitation planning.

3D geometrical models of bones, implants and other orthopedic devices are necessary input for other engineering technologies such as finite element method analysis, additive manufacturing, computer aided manufacturing, and artificial reality technologies, which include virtual reality (VR), augmented reality (AR), and mixed reality (MR).

In orthopedic practice, it is often the case that the orthopedist does not have a CT scan of the entire bone at his disposal, so planning the operation is difficult. The reason for this can be a major trauma, bone cancer or osteoporosis [12]. In such cases, reverse engineering technology is applied, the result of which is a 3D geometric model of the original bone. The method is based on artificial intelligence and a large number of samples of recordings of healthy bones of the same type. The accuracy of this method is very good and meets the requirements for the production of personalized implants, prostheses and scaffolds.

3.4 Finite Element Method

The finite element method (FEM) has numerous applications in orthopedics. One of its main uses is in the prediction of behavior of orthopedic implants, scaffolds and prosthetics, such as joint replacements, spinal implants, and bone plates. FEM can simulate the biomechanical behavior of the implant within the body, predicting how it will perform over time and allowing for optimization of its design. Also, FEM is used for multiscale computational modeling of bone tissue, which contributes not only to a better understanding of bone behavior, but also represents the basis for creating quality models for simulating the interaction between bone and implants [10].

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FEM makes a great contribution to personalized orthopedics in the optimization of the mechanical characteristics and shape of scaffolds and implants. This is achieved through a design study process during which, by changing the parameters and material of the implant or scaffold and successive FEM analyses, the optimal construction solution is reached [11] (Fig. 2).

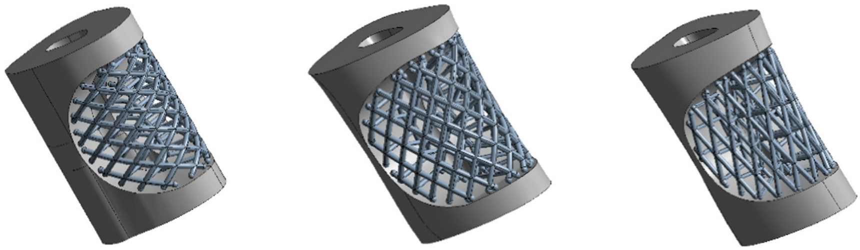

Fig. 2. Three instances of bone segment-scaffold assembly, in which struts angle was modified to take representative values of 32°, 52° and 72° respectively [11].

4 Conclusion

The strong progress of personalized orthopedics in the last thirty years has been achieved primarily through the application of various engineering technologies. Additive manufacturing, biomaterials, finite element method, medical imaging, virtual reality, robotics and artificial intelligence had the greatest impact.

All listed engineering technologies are in constant development. Thanks to them, an even faster development of personalized orthopedics is expected. We can expect growing use of additive manufacturing, not only for production of orthopedic devices but also in regenerative medicine. Regenerative medicine techniques, such as tissue engineering and stem cell therapies, may play a larger role in orthopedics in the future. These techniques may enable the regeneration of damaged or diseased tissues, reducing the need for traditional implants and devices. All this will be supported by the use of existing and further development of new biomaterials.

Also, we can expect increased use of artificial intelligence particularly in the areas of diagnosis and treatment planning. AI algorithms may be able to analyze patient data and medical images to identify patterns and predict outcomes, enabling more precise and individualized care.

As personalized medicine continues to expand and patient involvement increases, patients are anticipated to have a greater impact on their own healthcare. Wearable technologies like smartwatches, smartphones, smart clothing, smart glasses, and other sensors are expected to play a significant role in this development.

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Chapter 1

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