

Computational methods for biofabrication in tissue engineering and regenerative medicine - a literature review

Original

Computational methods for biofabrication in tissue engineering and regenerative medicine - a literature review / Bardini, Roberta; Di Carlo, Stefano. - In: COMPUTATIONAL AND STRUCTURAL BIOTECHNOLOGY JOURNAL. - ISSN 2001-0370. - STAMPA. - 23:(2024), pp. 601-616. [10.1016/j.csbj.2023.12.035]

Availability:

This version is available at: 11583/2984884 since: 2024-01-07T14:31:17Z

Publisher:

Elsevier

Published

DOI:10.1016/j.csbj.2023.12.035

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Review Article

Computational methods for biofabrication in tissue engineering and regenerative medicine - a literature review

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ARTICLE INFO

Keywords:

Computational biology
Optimization via simulation
Biofabrication
Tissue engineering
Regenerative medicine

ABSTRACT

This literature review rigorously examines the growing scientific interest in computational methods for Tissue Engineering and Regenerative Medicine biofabrication, a leading-edge area in biomedical innovation, emphasizing the need for accurate, multi-stage, and multi-component biofabrication process models. The paper presents a comprehensive bibliometric and contextual analysis, followed by a literature review, to shed light on the vast potential of computational methods in this domain. It reveals that most existing methods focus on single biofabrication process stages and components, and there is a significant gap in approaches that utilize accurate models encompassing both biological and technological aspects. This analysis underscores the indispensable role of these methods in understanding and effectively manipulating complex biological systems and the necessity for developing computational methods that span multiple stages and components. The review concludes that such comprehensive computational methods are essential for developing innovative and efficient Tissue Engineering and Regenerative Medicine biofabrication solutions, driving forward advancements in this dynamic and evolving field.

1. Introduction

Biofabrication is “the automated generation of biologically functional products with the structural organization from living cells, bioactive molecules, biomaterials, cell aggregates such as micro-tissues, or hybrid cell-material constructs, through Bioprinting or Bioassembly and subsequent tissue maturation processes” [1]. Tissue Engineering and Regenerative Medicine (TERM) is a challenging biofabrication application field bringing the promise to revolutionize the biomedical sector [2]. TERM applications require biofabrication products to be biomimetic, that is, to recapitulate the structural and functional features of their *in vivo* counterparts [3]. The degree of biomimesis in a product, based on the similarity of structural and functional features to physiological counterparts, determines its quality and clinical relevance. In biofabrication “the process is the product”, i.e., biofabrication processes and the resulting products are strictly intertwined, and so is their quality. Thus, ensuring product quality implies controlling process quality [4].

Quality control in TERM biofabrication requires analyzing the complex features determining the product quality, considering them as a function of defined critical process parameters [5]. Multi-technology biofabrication processes combine existing technologies to consider the

product’s relevant scales and aspects, maximizing product quality [6]. Automation and digitalization optimize the execution of existing biofabrication processes or parts [7]. Finally, searching for improved or new process schemes moves from inefficient trial-and-error paradigms to intelligent design [8].

Computational approaches play a role in each of these tasks. They work to harmonize multi-technology schemes with automation, optimizing existing processes and supporting rational research design. This harmonization helps better organize the experimental activity to make process improvement more efficient [6]. Besides enabling existing technologies and experimental designs to work together, computational approaches have untapped potential to innovate biofabrication process designs. To truly impact biomimetic quality, intelligent design approaches must rely on accurate models of biofabrication [9–11].

This work analyses the application of intelligent automation principles (Fig. 1.A) in modeling, design, and optimization (Fig. 1.B), with a focus on approaches combining simulation and optimization (Fig. 1.C) of TERM Biofabrication processes (Fig. 1.D). The following sections delve into various aspects of the field. Initially, Section 2 presents a bibliometric analysis that sets the stage for understanding the current scientific landscape. This is followed by Section 3, which examines and

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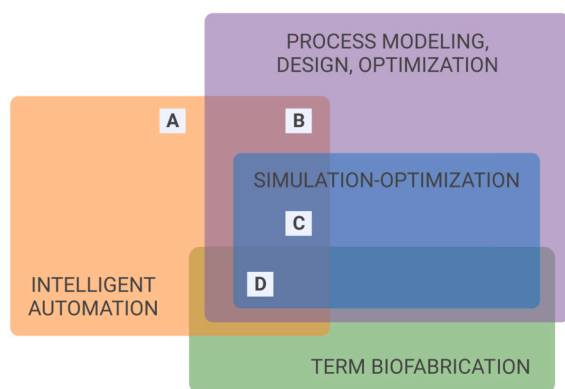


Fig. 1. This work presents a review of the scientific literature on works that, following the principles of Intelligent Automation (A), leverage Process modeling, design and optimization (B), and in particular Simulation-optimization (C) techniques for TERM Biofabrication processes (D).

evaluates the technological context relevant to computational methods in TERM biofabrication. Subsequently, Section 4 offers a comprehensive review of contemporary computational approaches in this domain, categorizing them according to the process stage they target. Finally, Section 5 synthesizes provided findings and discusses open challenges.

Statement of significance

Issue The central thrust of this review is to unveil the untapped potential of computational methods in enhancing the capabilities and outcomes of TERM biofabrication.

What is already known Several computational approaches exist for different stages of the biofabrication process, and existing reviews analyze them thoroughly. Yet, existing analyses lack focus on the role of accurate models of the biofabrication process in computational approaches to TERM biofabrication.

What this paper adds This work quantifies the relevance of the topic through the bibliometric and context analyses of the scientific domain of computational approaches to TERM biofabrication; subsequently, this work provides a review and analytical comparison of existing solutions organized by biofabrication process stage, including solutions based on accurate models of the biofabrication process.

2. The growing attention toward computational approaches: a bibliometric analysis

Attention toward computational methods is increasing in the biofabrication field. As illustrated in [12], several approaches exist to analyze a scientific landscape. This section enriches the study with a brief bibliometric analysis of the relevant scientific landscape. The analysis relies on PubMed¹ queries that combine keywords related to Biofabrication, TERM, and computational approaches, plus synonyms and adjacent terms to search publications on the platform.

2.1. Performance analysis

This analysis starts with the claim that the scientific community's interest in biofabrication and TERM is rapidly growing, supporting the relevance of the proposed work in analyzing state-of-the-art scientific production on the topic. Query 1.1 supports this claim by quantifying the interest in Biofabrication and Query 1.2 focuses the quantification

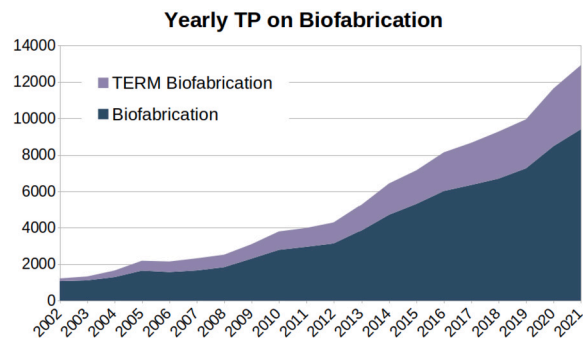


Fig. 2. Total Publications per year on Biofabrication, with an highlight on the contributions on TERM Biofabrication (Queries 1.1-1.2).

on TERM Biofabrication. Results were analyzed considering the period between 2002 and 2021 and using the Total Publications (TP) count as a performance metric [12].

Query 1.1 (Biofabrication): ("Biofabricat*" OR "Biomanufactur*" OR "Bioassembl*" OR "Bioprint*" OR "Biomaterial*")

Query 1.2 (TERM Biofabrication): ("Biofabricat*" OR "Biomanufactur*" OR "Bioassembl*" OR "Bioprint*" OR "Biomaterial*") AND ("Regenerative Medicine" OR "Tissue Engineering")

Query 1.1 retrieved 108,008 TP while Query 1.2 produced 28,549 TP, issued between 2002 and 2021. Fig. 2 shows a steady increase in yearly TP during the last two decades, indicating a growing interest of the scientific community in the field. The term Biofabrication, in general, reported 1,221 TP in 2002, growing up to 12,921 TP in 2021 with a 958% increase. Of these publications, the portion on TERM Biofabrication grew from about 12% of the total (149 over 1,221 TP) in 2002 to about 27% in 2021 (3,516 over 12,921 TP).

Considering the 28,549 TP on TERM Biofabrication, the analysis considered publications on computational approaches to TERM Biofabrication (Query 2.1), and more specifically on computational approaches to TERM Biofabrication based on either modeling or optimization (Query 2.2), finally narrowing down the focus on computational methods to TERM Biofabrication based on combined modeling and optimization (Query 2.3).

Query 2.1 (Computational approaches to TERM Biofabrication): ("Biofabricat*" OR "Biomanufactur*" OR "Bioassembl*" OR "Bioprint*" OR "Biomaterial*") AND ("Regenerative Medicine" OR "Tissue Engineering") AND ("In silico" OR "In-silico" OR "Comput*");

Query 2.2 (Computational approaches to TERM Biofabrication based on either modeling or optimization): ("Biofabricat*" OR "Biomanufactur*" OR "Bioassembl*" OR "Bioprint*" OR "Biomaterial*") AND ("Regenerative Medicine" OR "Tissue Engineering") AND ("In silico" OR "In-silico" OR "Comput*" AND ("Optim*" OR "Simulat*" OR "Model*"))

¹ <https://pubmed.ncbi.nlm.nih.gov/>.

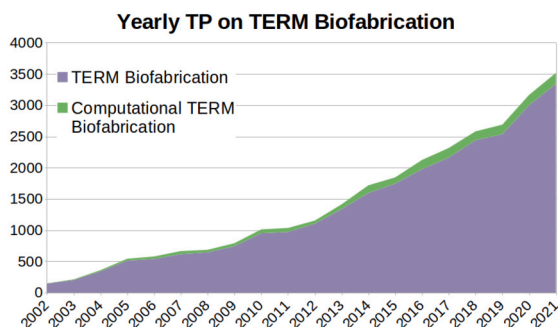


Fig. 3. Total Publications per year on *TERM Biofabrication*, with an highlight on the contributions on *Computational approaches to TERM Biofabrication* (Queries 1.2 and 2.1).

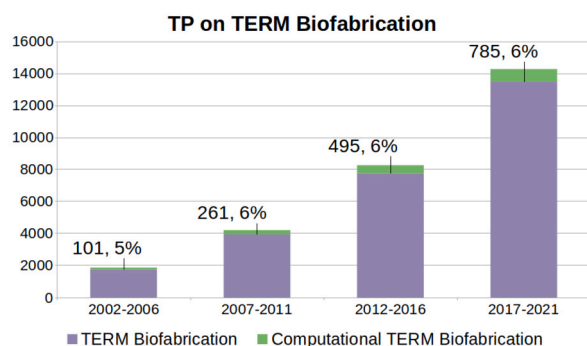


Fig. 4. Total Publications on *TERM Biofabrication* aggregated over five-year periods, with a highlight on the contributions on *Computational approaches to TERM Biofabrication* (Queries 1.2 and 2.1), that constitute between 5-6% of TP across all periods from 2002 to 2021.

Query 2.3 (Computational approaches to TERM Biofabrication based on modeling and optimization combined):
 ("Biofabricat*" OR "Biomanufactur*" OR "Bioassembl*" OR "Bioprint*" OR "Biomaterial*") AND ("Regenerative Medicine" OR "Tissue Engineering") AND ("In silico" OR "In-silico" OR "Comput*" AND ("Optim*" AND "Simulat*" AND "Model*"))

Starting from the result of Query 1.2, Queries 2.1-2.2 retrieved 1,642 TP for computational approaches to TERM Biofabrication (about 6%). Among these, 966 TP discuss computational approaches to TERM Biofabrication based on either modeling or optimization (about 60%). Fig. 3 shows the TP per year for TERM Biofabrication, highlighting the presence of scientific activity on Computational approaches to TERM Biofabrication in time, which constitutes 5% (101 publications) of TP between 2002 and 2006, and 6% (785 publications) for the period between 2017 and 2021, as illustrated in Fig. 4. Fig. 5 shows that publications on computational approaches to TERM Biofabrication based on either modeling or optimization constitute 50% (50 over 100 publications) of TP on computational methods to TERM Biofabrication between 2002 and 2006 and the 57% (785 publications) for the period between 2017 and 2021.

Finally, Fig. 6 illustrates the TP between 2002 and 2021 on computational approaches to TERM Biofabrication based on either modeling or optimization (Query 2.2, 966 TP), highlighting the contributions of computational methods to TERM Biofabrication based on combined modeling and optimization (Query 2.3).

2.2. Science mapping

After quantitatively analyzing publications in the reference scientific domains, this section aims to analyze and visualize the structure of

TP on computational approaches to TERM Biofabrication

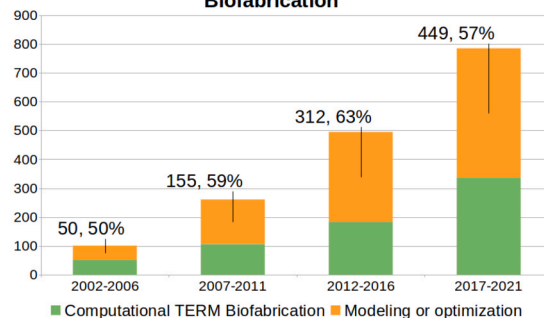


Fig. 5. Total Publications on *Computational approaches to TERM Biofabrication* (Query 2.1) aggregated over five-years periods, with a highlight on the contributions on *Computational approaches to TERM Biofabrication* based on either modeling or optimization (Query 2.2), that constitute 50% of TP between 2002 and 2007 (50 publications), grow to 63% for the period between 2012 and 2016 (312 publications), and decrease to 57% for the period between 2017 and 2021 (449 publications).

TP on computational modeling and/or optimization for TERM Biofabrication (2002-2021)

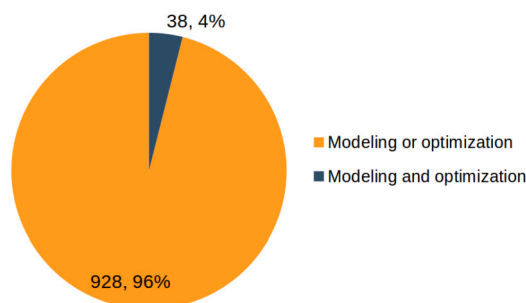


Fig. 6. Total Publications between 2002 and 2021 on *Computational approaches to TERM Biofabrication* based on either modeling or optimization (Query 2.2, 966 TP), highlighting the 4% (38 TP) on *Computational approaches to TERM Biofabrication* based on combined modeling and optimization (Query 2.3).

these domains by performing science mapping [13]. The analysis leveraged the VosViewer tool [14,15] to search publications on the PubMed platform [16]. The analysis focused on results of Queries 2.2-3 summarized in Fig. 5 and Fig. 6.

The first step of the analysis was constructing a co-occurrence network from the PubMed file generated with Query 2.2. The co-occurrence network emerged from text analysis of the *Title* and *Abstract* fields of each publication, then performing clustering analysis over the obtained network. Due to the high heterogeneity of terms in text data, this step employed a thesaurus file. Different versions of the same terms or concepts (plurals or singulars, synonyms, very close terms) were considered under the same umbrella term to facilitate network homogeneity and visualization.

Fig. 7 shows the text-based co-occurrence map based on Query 2.2. Different colors indicate separate clusters within the network. While the green cluster at the top includes clinical and biological concepts, the blue cluster at the bottom centers on technological approaches and research organization, and the smaller third cluster in orange contains terms related to biomaterial properties. Interestingly, terms about computational approaches exist in both the blue and orange clusters, with a predominance in the larger blue cluster. Fig. 8 provides an enlarged view over the portion of the map where terms referring to computational approaches emerge.

A simplified text-based co-occurrence map on Query 2.2 devising a different thesaurus file was also created to simplify situations where different concepts of the same domain group under the same

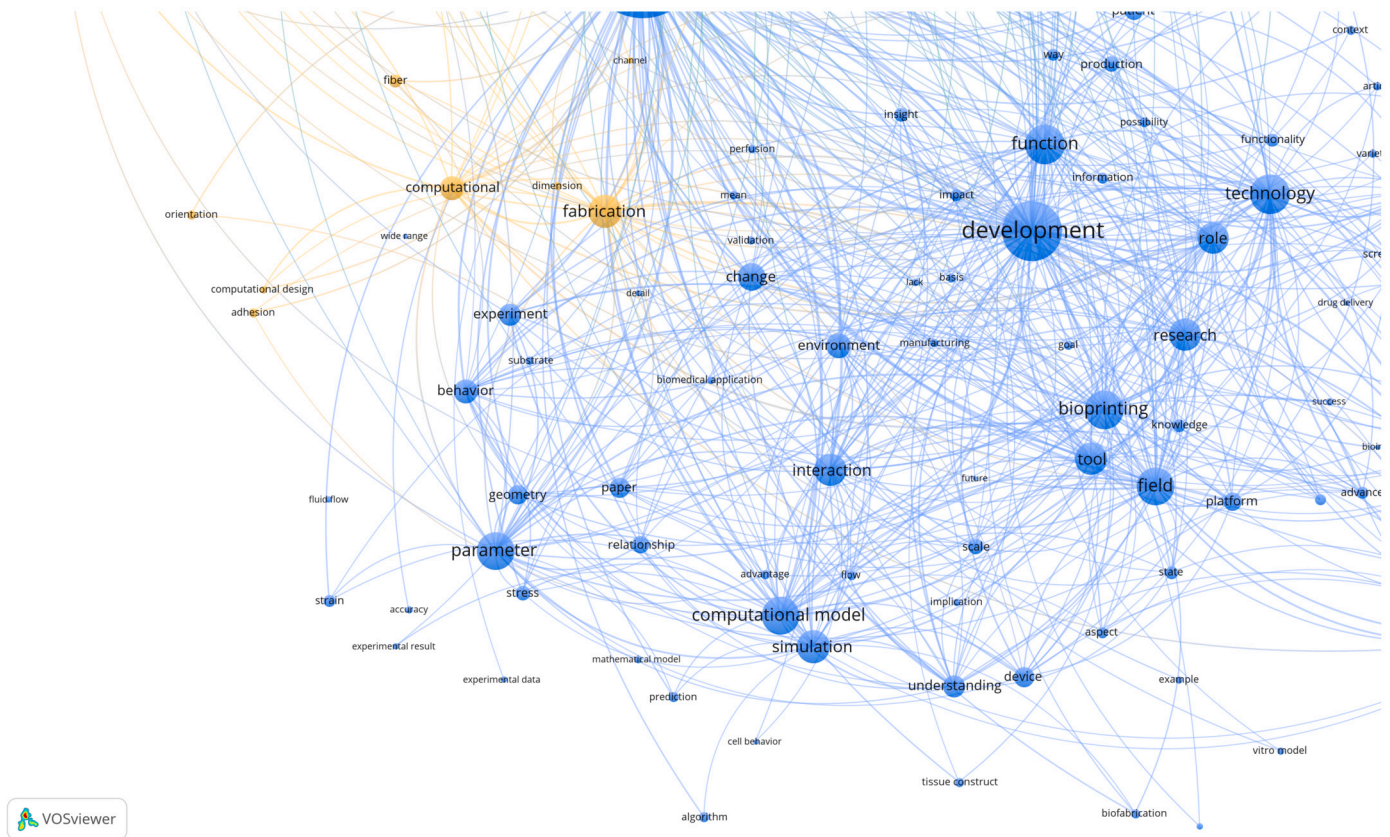


Fig. 8. Enlarged portion of the text-based terms co-occurrence map of Total Publications between 2002 and 2021 on *Computational approaches to TERM Biofabrication based on either modeling or optimization* (Query 2.2). The map is based on text analysis over PubMed files. It extracts co-occurrence information from the bibliographic database file obtained from the PubMed platform with Query 2.2 performing binary counting of terms occurrences over the Title and Abstract fields and considering the 60% most relevant terms among those occurring in at least ten documents (290 over 483). The relative size of nodes indicates term occurrences, and link strength indicates co-occurrences. Colors indicate the three different clusters in the network. Clustering relied on Association Strength as a normalization method and a Resolution parameter value of 1.00.

3. Computational methods for intelligent biofabrication: the technological context

In order to provide a context to this review, the following sections analyze the significant innovative trends in TERM biofabrication that are paving the way for extensive usage of computational methods in this field. In particular, they highlight the growing tendency of combining multiple technologies in biofabrication (Subsection 3.1), the increasing diffusion of automation and digitalization to optimize biofabrication processes (Subsection 3.2), the employment of research design techniques (Subsection 3.3) and finally the importance of comprising process complexity into computational approaches to biofabrication (Subsection 3.4).

3.1. Multi-technology biofabrication harmonizes combined capabilities

Biomimetic TERM products must replicate the complex and hierarchical structure of their *in vivo* counterparts. However, individual biofabrication technologies aim to control particular aspects of the final product. Such limitation appears even when considering a single class of technologies. Biomimetic scaffolds, for instance, must have a hierarchical architecture, including application-specific surface properties. However, each fabrication approach usually targets a specific resolution range, which limits fabricating hierarchical structures [2]. In order to overcome this limitation, hybrid biofabrication process schemes combine different fabrication approaches to expand the dimensional range covered and thus achieve biomimetic architectures [17].

Extending this reasoning to different classes of technologies, one can say that biofabrication approaches are today designed to control partial

aspects of the final product. For example, bioprinting approaches control spatial organization. Automated culture systems control functional maturation. Directed differentiation of cells governs the functional specialization of the biological building blocks for biofabrication.

Therefore, to control product quality, biofabrication processes can combine different technologies. Multi-technology biofabrication defines the combination of heterogeneous technological approaches, ranging from additive manufacturing to automation and computational process design, working together towards fully biomimetic TERM products [6]. Multi-technology biofabrication goes beyond combining different techniques, focusing more on their synergistic integration. Computational methods are crucial in enabling integration and rational harmonization in multi-technology procedures.

3.2. Automation and digitalization optimize processes

Biomanufacturing is moving towards fully integrating the Industry 4.0 principles in designing, executing, and optimizing manufacturing processes. Indeed, research automation and digitalization are spreading in the life sciences domain. For instance, fast biofoundries in synthetic biology are “*specialized laboratories that combine software-based design and automated or semi-automated pipelines to build and test genetic devices*” [18].

Several biomanufacturing applications rely on Robotic Process Automation (RPA), i.e., the use of a “pre-configured software instance that uses business rules and predefined activity choreography to complete the autonomous execution of a combination of processes, activities, transactions, and tasks [...]” [19,20]. Digitalization is a fundamental part of process

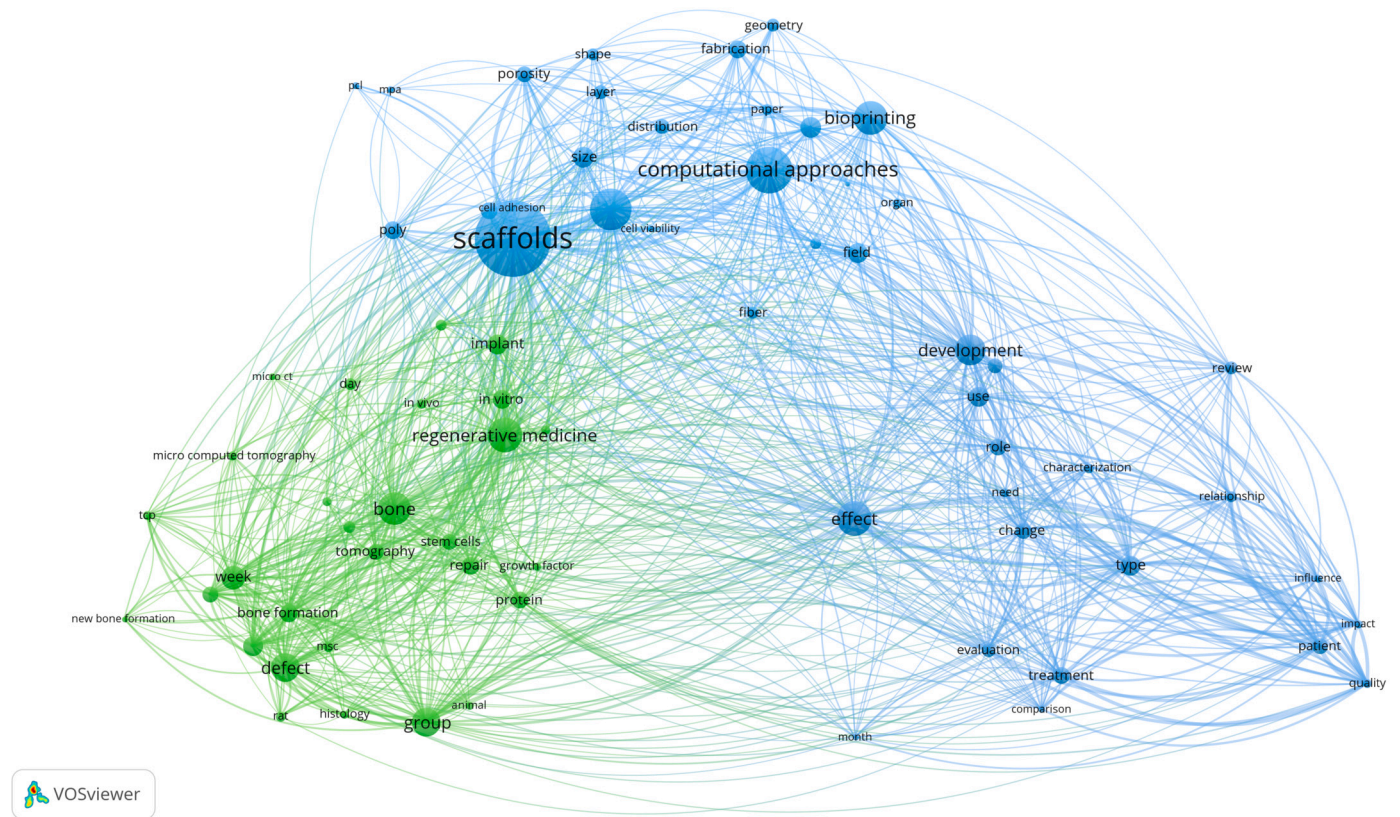


Fig. 9. Simplified text-based terms co-occurrence map of *Computational approaches to TERM Biofabrication based on either modeling or optimization (Query 2.2)*. The map is based on text analysis over PubMed files and extracts co-occurrence information from the bibliographic database file obtained from the PubMed platform with *Query 2.2* performing binary counting of terms occurrences over the *Title* and *Abstract* fields, and considering the 60% most relevant terms among those occurring in at least 30 documents (151 over 24820). The relative size of term nodes indicates total occurrences and link strength indicates co-occurrences. Colors indicate the three different clusters in the network. Clustering relied on Association Strength as a normalization method and a Resolution parameter value of 1.00.

automation, and it includes two main aspects: the *digitization* of existing operations and the creation of *digital twins* of existing processes. The *digitization* of existing laboratory processes is the transformation of analogical and manual operations into digital and semi-automated processes, i.e., the compilation of a laboratory diary or the acquisition and storage of newly collected data. Digitization and automation can work together to increase biofabrication process traceability, control, and quality [21].

Digital Twins (DTs) [22,23], are “complete virtual descriptions” of a physical process that are “accurate to both micro and macro-level” (adapted from [24]). They act as a digital counterpart of a physical process, dynamically modeling and analyzing it to actuate and modify the system in a risk-free environment, supporting new understanding and rational organizing of research activities. These technologies can serve different scopes in biomanufacturing, from version control systems for synthetic biology [25] to bioprocess modeling [26] and optimization [27]. DTs and computational approaches have a growing role in developing biomimetic TERM biofabrication products by supporting process execution optimization and intelligent process design [28,29].

3.3. Research design goes beyond empirical trials

Empirical methods face inherent limitations in exploring extensive and complex process design spaces due to the high resource costs and time demands associated with *in vitro* experiments. Automation and digitalization can enhance *in vitro* experimental campaigns by enabling a more significant number of experiments, thus broadening the exploration of the design space. However, adhering strictly to a trial-and-error experimental paradigm, even with these advancements, often leads to only incremental innovations, improving existing process de-

signs based on literature that might be incomplete, unreliable, and non-reproducible [30], and often chosen for popularity rather than performance [31].

Traditional trial-and-error methods, such as One Factor at A Time (OFAT) campaigns, that explore ranges of relevant system parameters one at a time [32], are costly in terms of time and resources. They also fail to recognize interdependencies among system variables, which hampers the ability to connect experimental results to realistic process designs. Actual designs control multiple variables simultaneously. These limitations result in OFAT yielding sub-optimal processes and products [23].

In contrast, factorial experimental design, which supports testing under multiple conditions, has proven effective in investigating optimal conditions for stem cell differentiation [33]. Design-of-Experiments (DoE) computational techniques [34,23] enable a more efficient, systematic exploration and exploitation of complex design spaces [32,8,35], showing adequacy in tackling multi-factorial problems in the optimization of directed cell differentiation [36,37] and in the development of tissue engineering scaffolds [38].

3.4. White-box models to optimize process design

Artificial Intelligence (AI) technologies offer the potential to automatically adjust experimental strategies as new data is generated, thereby maximizing information extraction and enhancing process improvement efficiency [7,39]. Computational tools and AI are instrumental in moving beyond traditional experimental trial-and-error methods [40,41], paving the way for the adoption of intelligent automation, which utilizes AI in automated and digitized processes to aid research design and result analysis [40,41].

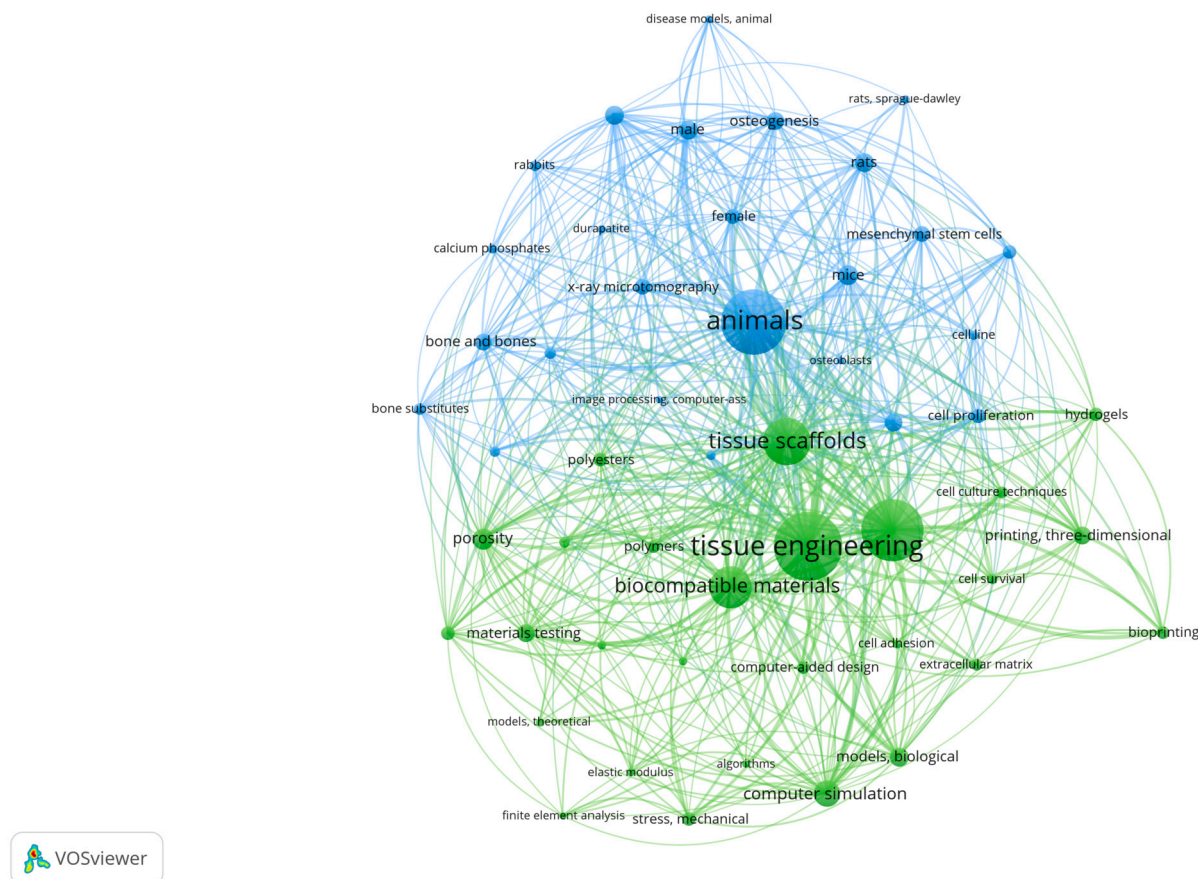


Fig. 10. Bibliographic data-based co-occurrence map of *Computational approaches to TERM Biofabrication based on either modeling or optimization* (Query 2.2). The map is based on a bibliographic analysis of PubMed files. It extracts MeSH keywords co-occurrence information from the bibliographic database file obtained from the PubMed platform with Query 2.2, performing Fractional counting of keyword occurrences and considering the ones occurring in at least 30 documents (52 over 1348). The relative size of nodes indicates keyword occurrences and link strength indicates the number of co-occurrences. Colors indicate the two different clusters in the network. Clustering relied on Association Strength as a normalization method and a Resolution parameter value of 0.8.

Computational Design Space Exploration (DSE) benefits from the integration of computational biofabrication models with optimization strategies, enhancing both research and process design by increasing the accuracy of bioprocess representation [34] and applying it for process optimization [7,39]. The design space of a biomanufacturing process is a multidimensional space defined by input variables and process parameters that influence product quality [5]. However, modeling the intricate biological complexity inherent in biofabrication processes presents substantial challenges to model-based DSE approaches.

In this direction, several computational approaches sustain biofabrication in general [29,42], and its process modeling in particular. While Machine Learning (ML) and Artificial Neural Networks (ANNs) offer black-box models of the system, computer simulations provide white-box models that capture mechanistic relationships and analyze complex dynamics under various conditions [43]. To support model-based DSE, white-box models of biofabrication must be accurate and predictive, as well as strike a balance between the holistic and hypothesis-driven modeling approaches.

Holistic modeling takes a comprehensive approach, encompassing numerous components and interactions, akin to viewing the entire system through a wide-angle lens. These models need to consider multi-level systems, from individual bioprocesses to multicellular aggregates [44], and are expected to support dynamic simulations of complex biological processes [45,46]. Although excellent for identifying emergent properties, the complexity of such models can be computationally intensive and come with many uncertain parameters [47]. High model complexity creates a vast and probabilistic design space, challenging both *in vitro* experimentation [48] and computational DSE.

Conversely, hypothesis-driven modeling focuses on testing specific aspects of the system [49], offering more targeted and manageable studies but potentially overlooking broader system interactions. This approach yields simpler models with lower computational demands, facilitating model-based computational DSE.

Ultimately, holistic and hypothesis-driven models respond to the challenge of incorporating biological complexity into biofabrication models. Both approaches can include the biological aspects of biofabrication processes to support their computational designs. Thus, both approaches or a combination thereof in hybrid models [50] provide valuable white-box modeling tools [49], with a positive impact on TERM biofabrication.

4. Computational methods for intelligent biofabrication: a review of state-of-the-art solutions

As thoroughly reviewed in [51], process design, modeling, and optimization find many applications to the different stages of TERM biofabrication. This section provides a review of the state-of-the-art computational methods applied to TERM biofabrication, including and not limited to the publications from Query 2.3 (see Section 2), focusing on techniques combining modeling and optimization methods. The review organizes around selected critical stages for TERM biofabrication [52], in particular: *Product modeling and quality control* (Fig. 12.A-E, Subsection 4.1), *Biomaterials qualification* (Fig. 12.B, Subsection 4.2), *Fabrication* (Fig. 12.C, Subsection 4.3) and *Maturation* (Fig. 12.D, Subsection 4.4).

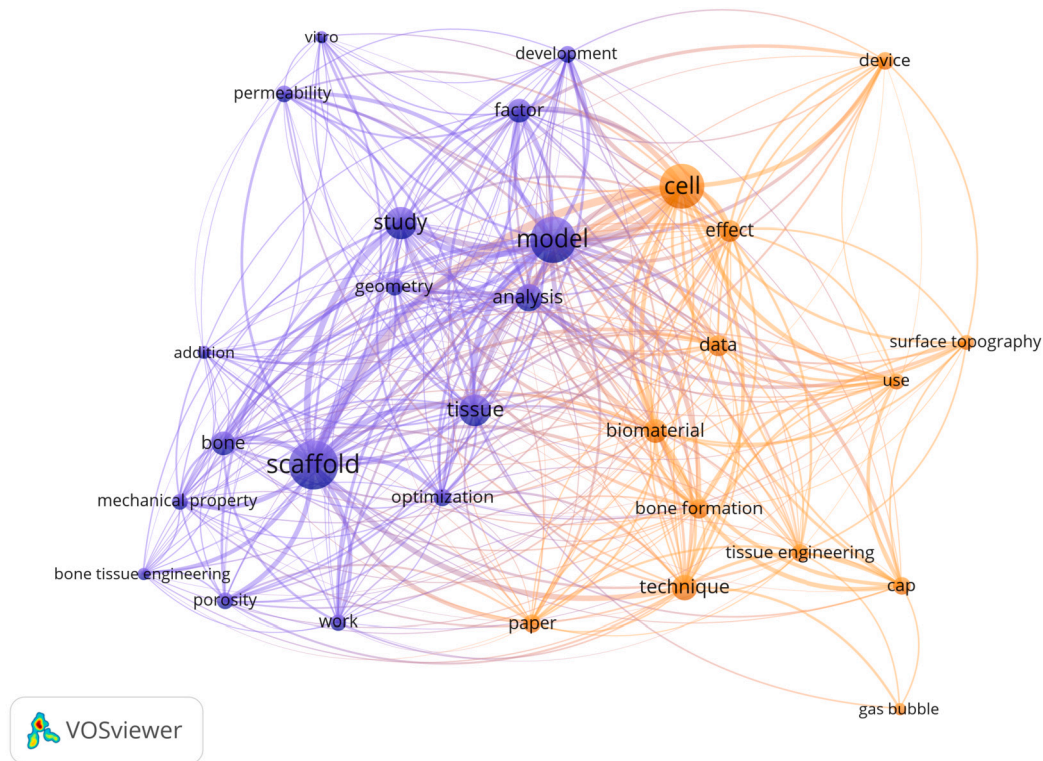


Fig. 11. Text-based terms co-occurrence map of *Computational approaches to TERM Biofabrication based on modeling and optimization combined* (Query 2.3). The map is based on text analysis over PubMed files. It extracts co-occurrence information from the bibliographic database file obtained from the PubMed platform with Query 2.3 performing full counting of terms occurrences over the *Title* and *Abstract* fields and considering the 30 terms occurring in at least six documents. The relative size of term nodes indicates total occurrences and link strength indicates co-occurrences. Colors indicate the two different clusters in the network. Clustering relied on Association Strength as a normalization method and a Resolution parameter value 0.70.

4.1. Product modeling and quality control

Product modeling (Fig. 12.A) aims at defining the target product from expert knowledge or following a data-driven process using medical imaging to determine the desired features in the product. Quality control (Fig. 12.E) assesses the presence of the desired functional and structural features defined in the product model, especially if biofabrication has a biomimetic purpose (Fig. 12.A). Product modeling includes retrieving and using information on the product, its design, and the definition of the desired features. The ultimate goal of TERM biofabrication is fulfilling a patient's clinical need for regeneration. This goal implies that a biofabricated product must be biomimetic; that is, it must faithfully recapitulate the biological structures to regenerate. This principle guides the product design and modeling and defines quality metrics for the biofabrication products obtained. In particular, for TERM applications, the quality of the product is often reflected in biomimetic fidelity to its *in vivo* counterpart since the ultimate goal is regeneration.

4.1.1. Data-driven reconstructions

Computational tools support automated data-driven modeling of the functional and structural features to replicate the natural system, increasing biomimetic fidelity in a TERM biofabrication product. Image-based Computer-Aided Design (CAD) models can build on processed images acquired directly from patients, including Magnetic Resonance Imaging (MRI) or Computed Tomography (CT) scans that are later converted to Digital Imaging and Communications in Medicine (DICOM) format [53] and then to Standard Tassellation Language (STL) files for printing [54]. This process finds application in orthodontic regeneration [55] and soft-tissue engineering [56] as well as in the generation of three-dimensional (3D) heart valves [57].

However, tissue images *per se* fail to provide information at the single-cell level. Thus, reconstructed 3D tissue models usually lack multi-scale cellular resolution and tissue- or organ-specific properties.

Computational methods support the development of TERM product models beyond image processing, by allowing the discovery of tissue architectures from imaging and spectral data, bridging the information from the *in vivo* tissue microenvironment to the construct properties at the scale that the bioprinting technology chosen can fabricate [58]. To this aim, Deep learning (DL) super-resolution unsupervised approaches [59] can transform low-resolution images into higher-resolution versions, narrowing the gap between the average resolution of medical images on the millimeter scale and the resolution of bioprinting technologies, which lies on the micrometer scale [60]. This transformation allows extracting biological features at the cellular level in an unbiased and data-driven manner. For example, authors in [61] leveraged a Convolutional Neural Network (CNN) to classify cells according to their cell cycle phase. These initiatives support the data-driven construction and enrichment of Intelligent Digital Twins (IDTs) comprising a multi-scale model of the target products' architectural and functional features, for which is crucial to build and curate supporting databases [62].

4.1.2. Computer-assisted design

CAD is a technology used for creating precise two-dimensional (2D) and 3D models of physical components, widely used in industries such as engineering, architecture, and manufacturing. It improves design accuracy and efficiency and facilitates easy modifications, often integrating with other technologies like Computer-Aided Manufacturing (CAM) and 3D printing for simplified product development. Bio-CAD, bio-CAM, and bio-CAE apply CAD, CAM, and Computer-Aided Engineering (CAE) to biological processes and subprocesses. The bio-CAD process supports the design of tissue and organ blueprints, the bio-CAM method the manufacturing of biological products, and the bio-CAE the

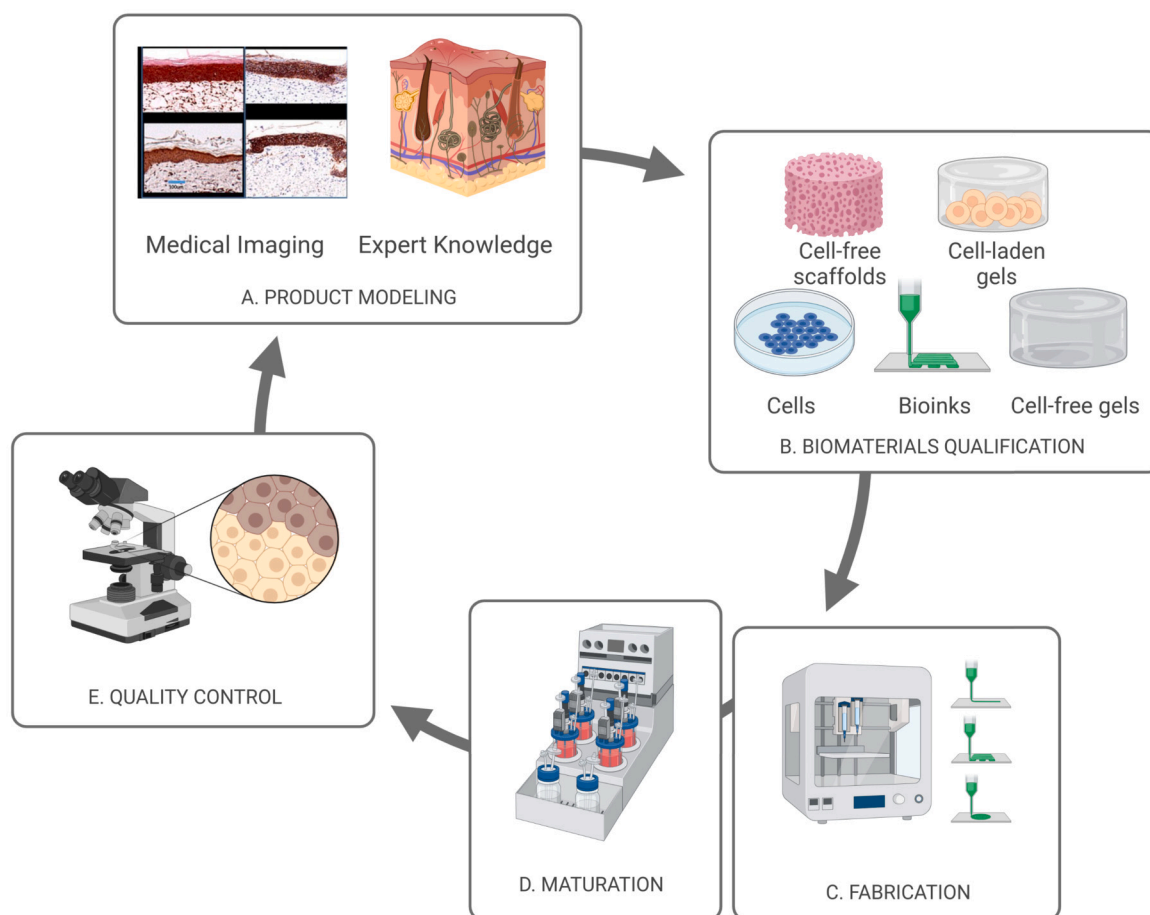


Fig. 12. Overview of a biofabrication process: (A) medical images and expert knowledge define a model for the target product, which guides the (B) choice and combination of biomaterials and cells used for (C) fabrication via bioprinting and bioassembly, followed by (C) construct maturation; (D) evaluation of the quality of the mature product relies on measuring its closeness to the structural and functional features of the defined target.

creation of complex architectures, and the validation and optimization of biomanufacturing tools and bioproducts [63,64]. CAD is the most widely employed method for designing scaffolds from scratch or using 3D scans of the target biofabrication product [65], and supports the design of scaffolds providing the localized control of biomolecules distribution for tissue engineering and drug release [66].

Bio-CAD models also rely on computational methods. Several approaches exist to translate a model into a physiologically relevant product through computer-controlled Rapid Prototyping (RP) [67–69]. Computational modeling of tissue- and organ-level biological complexity combine with bio-CAD to embed complex functionality into TERM products, optimizing them and increasing their quality. For instance, ML techniques predict material properties related to various mixture compositions of the bio-inks and support scaffold designs by learning from an extensive database of materials and designs [70,71]. ML also supports multi-objective optimization of material process variables [72].

Biofabrication products are poised for subsequent maturation, adapting to the stimuli received during maturation. Thus, product design must consider the cellular component's role in the product's evolution to its final form, requiring consideration of the product's evolution after the initial construction and under different environments. Computational approaches support this by guiding product design considering potential functional responses to different stimuli [73], following the four-dimensional (4D) printing paradigm [74], producing dynamic structures whose functionality, shapes, and properties change based on the environmental inputs. Since cells are the main actors of transformation and response to the environment, product design

must consider their behavior in predicting the final product form. Computational tools help in this by modeling intracellular, cell-cell, and cell-biomaterials interactions during fabrication [62] and subsequent maturation [75–77].

This concept finds unique declination according to the specific biofabrication product and regenerative application. For example, integrating computational modeling in heart valve design could predict long-term in vivo performance, remodeling, and failure under non-physiological pressure loading in a translational sheep model [78]. Bioprosthetic heart valve (BHV) presents unique challenges for computational design: standard Finite Elements Methods (FEM) can simulate the effect of hydrostatic forcing on a closed BHV, but this approach fails to account for transient responses during valve opening and closing. Nonetheless, the latter effects are not negligible since they contribute to long-term structural fatigue and thus to the risk of BHV transplant failure. Thus, BHV computational design must rely on models of the surrounding hemodynamics that support the accurate simulation of these effects, as provided in [79], where authors propose a complete mechanical model of a BHV based on the immersogeometric Fluid-Structure Interaction (FSI) methodology.

In conclusion, computational methods support the product design and quality in TERM biofabrication by automated data-driven extraction of target product features and by handling the complex computer-assisted design of dynamic products that evolve independently and after complex responses to environmental stimuli.

4.1.3. Scaffolds

Porous scaffolds for TERM products must have certain biological, biomechanical, and biomaterial-related functionalities, including suitable pores size and geometry, allowing nutrients to diffuse uniformly and cells of the engineered tissue to invade the scaffold. Secondly, scaffold surfaces must have physical-chemical properties, ensuring biocompatibility; that is, they must allow cells to adhere and develop the expected phenotypes. During fabrication, scaffold material must exhibit mechanical properties supporting the bearing of required loads during regeneration. Finally, scaffolds must be biodegradable or bioabsorbable once sufficient tissue has formed to guarantee mechanical support to the TERM product.

The role of computational methods in scaffold fabrication is to identify optimal trade-offs considering this set of complex requirements [80,38]. Moreover, the comprehensive analytical and numerical modeling of the 3D and 4D additive manufacturing benefits biofabrication with understanding, predictive modeling, and optimization of the bio-fabrication process at different scales [81].

Most computational approaches in the literature target optimizing the mechanical and chemical properties of bone graft scaffolds [82], including porosity, micro-architecture, Young's modulus, and dissolution rate. In [83], the authors propose a general design optimization scheme for 3D internal scaffold architecture to find a good trade-off between elastic properties and porosity. They introduce the homogenization-based topology optimization algorithm, demonstrating that the method can produce biomimetic structures mimicking anisotropic bone stiffness obtained with scaffolds of widely different porosity. In [84], authors propose a 3D computational model based on Sussman–Bathe hyper-elastic material behavior to study interpenetrated polymer networks for cartilage repairing, quantitatively simulating the distribution of fluid fluxes and nutrient supply within the different regions of a construct.

While these properties are pivotal for scaffold quality, considering cell-material interactions is crucial to the modeling and designing of TERM bone grafts. Computational design must account for the influence of growth factors and other biochemical signals and the accurate simulation of dissolution processes, including the impact of degradation products such as calcium ions and inorganic phosphate on bone formation biological processes. In bone tissue engineering, the passage from scaffold design to manufacturing requires compliance with the design control requirement that must undergo verification in a finished device. Authors in [85] propose a computational approach to investigate the accuracy of the final properties of polycaprolactone scaffolds fabricated by selective laser sintering [86].

On the structural optimization front, Topology Optimization (TO) aims to optimize scaffold printing by organizing material placement in space. For instance, different TO approaches such as Solid Isotropic Material with Penalization (SIMP) [87], Bidirectional Evolutionary Structural Optimization (BESO) [88], and level-set [89] support the design of differentially dense and stiff structures. In [90], authors leverage TO on the performance of a chitosan hydrogel bioprinted soft actuator while maintaining the material's volume fraction. Triply periodic minimal surfaces (TPMS) recently inspired the fabrication of biomimetic porous scaffolds since they support cell adhesion, migration, and proliferation. A versatile design method for TPMS sheet scaffolds, which can satisfy multiple requirements simultaneously, was proposed in [91]. In these applications, TO does not consider cell-related aspects: optimized parameters only involve a single scale and cell-free biomaterials.

However, the geometric properties of scaffolds for tissue engineering directly affect cellular deposition. Computational tools sustain the design of scaffolds with varying controlled geometrical and functional properties throughout their structure [92,93], such as varying porosity [94]. Models of cellular behavior can help choose geometrical properties ranges to use for scaffolds. For example, computational models of osteoblasts support the prediction of the growth of bone matrix tissue in scaffolds with different pores geometry [95].

Nevertheless, TO approaches easily extend to cell-laden and multi-scale biomaterials. For instance, in [96], authors present a level-set-based topology optimization algorithm and a time-dependent shape derivative to optimize scaffold architecture for femur models, showing significant advantages in continuing bone growth compared to stiffness-based topology optimization, time-independent design, and typical scaffold constructs. The common usage of topology optimization and models of biological responses to different scaffold properties prove effective in supporting scaffold design [97]. In [98], authors leverage Three Dimensional Convolutional Neural Network (3D-CNN) surrogate models to optimize multi-scale topology on non-parametric micro-scale structures. Authors in [99] present different computational approaches, including surface hit detection and ordering and prediction of relevant surface properties and cell responses, aiming at optimizing surfaces to influence cell behavior.

In this direction, FEM is a powerful modeling and optimization tool for biomechanical research [100–104], which supports the modeling of not only biomechanical and geometrical aspects of the cell-free scaffold, but also of dynamical features and the responses of specific cell types during later construct maturation [105]. Authors in [106] optimize geometrical features of scaffolds, maximizing bone growth rate with an algorithm relying on parametric Finite Elements (FE) models of scaffolds, computational models of cells, and optimization methods.

Similarly, reaction-diffusion models [107] support the evaluation of geometric and mechanical properties of scaffolds [108], as well as the rational design of waveguides for cells within biomaterials [109]. The computational simulation of 3D bone tissue regeneration based on the voxel FE method, including new bone formation and scaffold degradation, is at the core a model-driven computational framework for designing and optimizing a porous scaffold microstructure in [110].

Computational modeling of the bone formation process helps design optimal combinations of calcium-based biomaterials and cell culture conditions to maximize the quantity of formed bone in [111]. FE analysis, Computational Fluid Dynamics (CFD) and mathematical modeling support the choice of optimal mechanical properties of a scaffold for cartilage regeneration [112,113]. The simulation of matrix degradation processes informs the fabrication of a cartilage-like construct to study cartilage degradation in osteoarthritis in [114].

Considering cardiovascular applications, a notable example is scaffolds for *in situ* cardiovascular tissue engineering. This approach uses a synthetic, biodegradable scaffold as a temporary framework for incoming cells to develop their own Extra-Cellular Matrix (ECM), which gradually breaks down, allowing tissue regeneration. Computational models are pivotal in factoring in the role of incoming cells in product quality, directly impacting the clinical outcome [115].

Vascularization of constructs is still a major limiting factor in the size and quality of TERM products. Computational design must comprise the multiple interdependent regulatory mechanisms in the cross-talk between endothelial cells and native tissue cells to recapitulate the formation of new functional blood vessels. A computational model of vascular adaptation and a formal optimization method support tissue-engineered vascular graft design in [116]. Computational simulations and microvascular network analysis supported optimization of the geometry and oxygen distribution within hydrogel constructs in [117].

Scaffolds are crucial in fabricating biomimetic liver models [118, 119]. Computational modeling finds application in the characterization of vascular load in scaffolds for liver engineering for their rational design [120,121].

For wound healing applications, computational tools support the image-based automatic structural design of scaffolds and localized control of biomolecule distribution to sustain healing over time [66,122].

Another example of the unique challenges posed to scaffold design by different TERM applications is nerve regeneration. The computational design allowed exploring the impact of various structural features on their properties to increase biomimicry and optimize porosity and

permeability for the design of nerve guidance conduits, tubular tissue engineering scaffolds used for nerve regeneration [123].

In conclusion, computational methods support scaffold design and optimization in TERM biofabrication by automatically finding optimal trade-offs between application-specific requirements, which also extends to the requirements posed by the complex cellular processes they host.

4.2. Biomaterials qualification

The definition of the product model guides the selection of biomaterials and cells to employ (Fig. 12.B). TERM biofabrication relies on either the bioassembly of building blocks based on living cells, bioprinting of biomaterials, or a combination of the two [124] (see Subsection 4.3). Therefore, the qualification of inorganic and organic biomaterials used for these two processes dramatically affects the quality of the final product. The specific combinations of biomaterials must carefully adjust to the scopes and machinery available for biofabrication. For example, a bio-ink must be biocompatible with the cell type to be printed and printable using bioprinting technology. Cells for preparing cell-laden materials or seeded in cell-free scaffolds undergo selection, culture, and differentiation before fabrication. Computational tools sustain such biomaterials' rational design and development in several ways, combining the non-trivial composition of multiple mechanical and biological properties, which often conflict.

4.2.1. Inorganic biomaterials

Computational approaches support biomaterials characterization and explore optimal trade-offs between different desired features of biomaterials. A notable example in bioprinting is the trade-off between the degree of biocompatibility for the cells employed and the printability, considering the bioprinting technology of choice. Failure Modes and Effects Analysis (FMEA) and Quality Function Deployment (QFD) support the identification of functional requirements for a specific application in the design of a new biomaterial. In contrast, Multi-attribute Decision Making (MADM) approaches support selecting the best constituent materials to employ. The combination with DoE allows searching the biomaterial design space efficiently, saving on experimental resources [125,126].

Extending these approaches, Multi-objective Decision Making (MODM) tackles biomaterial design problems that seek to satisfy multiple goals concurrently, e.g., adequate stiffness and degradation properties in bone scaffolds.

Computational multi-objective optimization provides multiple optimal solutions. Computational models of biomaterials support DSE by testing the optimal solutions *in silico*. For example, a model of viscoelastic materials mimicking soft biological tissues demonstrates its capability to capture complex viscoelastic behavior observed experimentally [127]. Such accurate, validated models of physical and chemical biomaterial behaviors support the computational testing of the generated optimal solutions to prioritize subsequent experimental tests further, saving time and resources.

This reasoning extends to cell-laden biomaterials. Embedding computational models of biological components into biomaterial design and optimization for the design of biomaterials, providing more accurate and comprehensive product quality prediction, further minimizes the experimental costs of iterative material synthesis and testing [38]. In this direction, modeling of organic and inorganic components, combined with optimization solutions, supports the characterization and the choice of optimal biomaterials composition given a specific TERM application. For example, FE modeling and optimization support the characterization of polyvinyl alcohol as a potential biomaterial for cartilage tissue engineering scaffolds in [128]. The joint consideration of both inorganic substrates and cellular components allowed the creation of an *in silico* design library based on numerical modeling to predict

composite biomaterials performance and support their design, applying it to articular cartilage engineering for patients in [129].

4.2.2. Organic biomaterials

While several computational approaches target the design and optimization of inorganic biomaterials, factoring in their interactions with cells, other approaches focus on the cellular component only, in particular, to guide the selection, design, and culture of cells and cell aggregates such as spheroids.

Computational approaches play a pivotal role in the strategic selection of cell strains for TERM biofabrication. Within this realm, cells are frequently sourced from the patient themselves, necessitating careful consideration regarding the types of cells to utilize. This involves making informed decisions about directing the differentiation processes of patient-derived induced Pluripotent Stem Cells (iPSC) towards specific cell types for regenerative applications. In this direction, computational methods proved capable of supporting the design of directed differentiation or transdifferentiation processes of cells. A computational framework that combines gene expression data with regulatory network information can predict the reprogramming factors necessary to induce cell transdifferentiation for TERM applications [130]. Furthermore, another computational framework is the base of a design tool for finding combinations of signals efficiently inducing cell conversions based on a stochastic gene regulatory network model embedding information on the transcriptional and epigenetic landscape of cells in [131].

Self-assembled 3D cell spheroids can replicate tissue functionality, working as building blocks for TERM products and supporting *in vitro* tissue maturation before fabrication by bioprinting or bioassembly, increasing the efficiency of overall fabrication processes of TERM products. Computational methods sustain the rational fabrication of spheroids to tune them to specific application needs. For example, computation combines with experimental activity to support the modulation of non-geometrical parameters in the design of the fabrication process of 3D articular chondrocytes spheroids. In contrast, CFD modeling underlies the optimization of geometrical features of the culture chip, modulation of cell-related features such as cell concentration, flow rate, and seeding time to model cell trapping follows in [132].

In conclusion, computational methods support biomaterials qualification for TERM biofabrication by sustaining the rational choice and combination of inorganic and organic constituents of biomaterials, taking into account biological requirements to optimize inorganic biomaterials, as well as the delicate nature of biological components in cell-laden constructs.

4.3. Fabrication

Fabrication of spatially-organized TERM constructs (Fig. 12.C) employs raw cells and biomaterials and relies on various techniques. Among them, this review focuses on bioprinting and bioassembly. Bioprinting is “the use of computer-aided transfer processes for patterning and assembling living and non-living materials with a prescribed two- or three-dimensional (2D or 3D) organization to produce bioengineered structures serving in regenerative medicine, pharmacokinetic and basic cell biology studies” (adapted from [133]). Bioassembly is “the fabrication of hierarchical constructs with a prescribed 2D or 3D organization through the automated assembly of pre-formed cell-containing fabrication units generated via cell-driven self-organization or through the preparation of hybrid cell-material building blocks, typically by applying enabling technologies, including microfabricated molds or microfluidics” [1].

4.3.1. Printing process

Bioprinting applies to both inorganic scaffolds and cell-embedded bioinks. The computational optimization of bioprinting processes potentially has various objectives [58]. Some endeavors aim to maximize printing fidelity: the similarity between the product models and the

actual bioprinted product. Other approaches maximize biomimetic fidelity: the construct's biological, mechanical, and rheological similarity to its *in vivo* counterpart. Other approaches tackle the challenge of the joint optimization of printing and biomimetic fidelity in bioprinting. For example, computational analysis underlies the tuning of flow parameters to optimize needle geometry for the biofabrication of high-resolution, fragile cell transfer of printed human iPSC with a low-cost 3D printer for precise cell placement and stem cell differentiation in [134].

Several computational DoE approaches target the optimization of significant process parameters in Fused Deposition Modeling (FDM), a rapid additive manufacturing prototyping technique [135]. DL methods proved able to optimize the bioprinting process by elucidating the complex relationships among the various printing parameters and predicting their optimal configurations for specific objectives [136,137,60]. For example, a multi-objective optimization approach improves printing accuracy and stability in [138]. In contrast, a ML approach underlies effective and accurate drop-on-demand printing control in [139]. Computational methods also sustain quality control in the printing process. For example, a CNN supports the data-driven detection of printing anomalies towards real-time process adjustment to ensure high printing quality in [140].

Computational optimization also targets the design of fabrication processes and systems. A fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) Multi-criteria Decision Making (MCDM) process allows for identifying the best bioprinting process to optimize the biomechanical properties of the construct given a starting printing material in [141]. Multi-physics computational models support the design of an extruder system for the biofabrication of vascular networks, intending to maintain cell viability during the printing process [142].

4.3.2. Cell seeding

Maximizing the number of cells uniformly occupying the available space within scaffolds facilitates tissue culture functionality and reduces tissue maturation time. Thus, cell seeding is a critical step in the biofabrication of TERM products. Computational methods combine with experimental activity to design effective cell seeding techniques. For instance, a combination of FEM to predict the scaffold permeability effects on cell seeding effectiveness and a fully factorial experimental design allowed to assess the relative importance of permeability, thickness, and coating on cell seeding efficiency and uniformity in [143]. As an additional example, the simulation of the cellular interactions with biomaterials, cells, and dynamic media in a scenario where cell seeding occurs under perfusion conditions helped to optimize the seeding time, and the number of cells seeded in the scaffold in [144].

4.3.3. Spheroid bioassembly

Spheroid fusion, the aggregation of spheroids into larger constructs, is an approach for efficiently constructing larger tissues. With the increase in construct size, oxygen, and metabolites are no longer uniformly accessible to cells across the construct, hampering their viability and thus the quality of fabrication products. Computational methods support modeling cellular needs during spheroid-dependent fabrication, predicting their viability under different process parameters. For example, a hybrid discrete-continuous heuristic model, combining a cellular Potts-type approach with field equations, describes metabolic effects over cells during spheroid-dependent fabrication in [145].

In conclusion, computational methods sustain the multi-objective optimization of the fabrication stage of TERM biofabrication by navigating complex trade-offs between fabrication parameters, benefiting from the explicit modeling of the role of cells in ensuring final product quality. This advantage applies to both inorganic and organic components of fabricated products.

4.4. Maturation

Automated culture systems include different technologies ranging from microfluidic devices to bioreactors (Fig. 12.D), which automatically administer signals to guide product maturation towards the desired structural and functional features. In biofabrication, the maturation stage is a critical stage where the biofabricated structures undergo cellular development, differentiation, and extracellular matrix formation to achieve functional characteristics akin to natural tissues [52]. The dynamical modulation of environmental stimuli administered to the construct affects product maturation and, ultimately, the emergence of the desired functional and structural features. Computational methods support the characterization and design of the maturation process, allowing prediction of how the administered stimuli make the desired features emerge [146]. For example, DL approaches to support the prediction of functional activations from environmental stimuli of different kinds [60]. ANNs predicted the induction of osteogenesis from sets of biomechanical loading parameters values [147]. Computational approaches also target the overall biofabrication process design by predicting the final product features and the respective product quality based on the set of administered stimuli and their organization in time and space.

For example, modeling the identity and quality of stimuli, including their complex behavior in the physical environment, combines with experimentation to link biological responses to mechanical stimulation, improving the understanding of the cause-effect relationship of mechanical loading in [148].

As a notable computational approach, SIMulation using Metropolis Monte Carlo method (SIMMMC) supports the 3D modeling of specific biological systems, including living cells and biomaterials, and simulates construct evolution from the structural and functional perspective, based on the Metropolis Monte Carlo (MMC) modeling of living cells, biomaterials, and cellular medium [149].

Maturation often relies on automated culture systems such as bioreactors of varying sizes and designs. Computational methods support the optimization of bioreactor design. For example, CFD modeling allows the optimization of the flow profile when designing the perfusion chamber of a perfusion bioreactor system to engineer human cartilage grafts in [150].

Construct maturation's success in bioreactors relies heavily on cell viability and proliferation. Computational models of the micro- and the macro-scale combine with CFD to simulate cell colonization processes in a perfusion bioreactor and perform model-based optimization of the perfusion flow rate to maximize cell colonization in [151]. A model of tissue growth inside 3D scaffolds in a perfusion bioreactor combines with a multi-objective optimization method to find the most cost-effective medium refreshment strategy for maximizing tissue growth while minimizing experimental costs in [152]. Discrete simulation of intra- and extracellular processes combines with evolutionary computation to perform the DSE of process designs to generate optimal biofabrication protocols to maximize size and control geometry of human epithelial monolayers *in silico* in [153]. Continuous simulation of tissue dynamics based on vertex models of cells (leveraging on the Palacell2D simulation framework [154]) combine with a deep Reinforcement Learning (RL) approach to generate optimal protocols for epithelial sheets culture for maximizing the total number of cells produced and optimizing the spatial organization within the cell aggregate in [155].

In conclusion, computational methods support the maturation stage of TERM biofabrication by modeling the dynamic processes taking place within the developing construct and predicting the effect of the administered stimuli over them to explore several process outcomes and support the choice of optimal process designs for specific target products.

5. Open challenges and future trends

This review aimed to present computational methods for modeling, designing, and optimizing TERM biofabrication processes, with a focus on encompassing biological complexity through diverse modeling approaches from holistic to hypothesis-driven. The predominance of TERM bone or cartilage engineering in publications aligns with science mapping results (Section 2), while the infrequent application in more complex tissue or organ biofabrication reflects current limitations in mimicking biological complexity (Section 1). Despite these limitations, computational tools show promise in advancing the biofabrication of complex TERM products, thus expanding the range of regenerative applications. However, current computational models often simplify the intricate relationship between organic and inorganic components in biofabrication or focus narrowly on single process aspects, limiting their impact on process design and product quality.

To fully realize the potential of computational optimization in TERM biofabrication, a truly interdisciplinary approach is necessary, incorporating diverse scientific and technological elements and addressing the underlying biological complexity for holistic process modeling, design, and optimization, while developing strategies to improve their computational feasibility. In particular, future computational methods in TERM biofabrication should address the following key challenges.

Interdisciplinary enabling: Computational methods must become facilitators of interdisciplinary collaboration, catering to the varied scientific backgrounds of researchers in TERM biofabrication [1]. They should ensure usability and accessibility, promoting findability and direct reusability of solutions [156] to accelerate collaborative scientific advancement. The sharing of novel solutions should leverage on scientific reproducibility tools like Docker or Singularity container platforms [157]. In general, novel methods shall truly enable interdisciplinary collaboration, to mediate the synthesis of diverse perspectives into models, and providing modular and reusable solutions for model-based optimization.

Intrinsic flexibility: Computational methods must adapt to new biofabrication processes and targets, especially in optimizing clinically relevant products. They should support personalized medicine principles, adapting to specific patient needs [158–160] and the complex normative scenario for clinical translation [161,162]. Future approaches shall reach extensive flexibility over of patient- and regulation- dependent constraint specifications to seamlessly adapt to different clinical applications.

Multi-component modeling: computational methods must rely on accurate models of the several inorganic and biological components in biofabrication [2,6], accurately predicting cellular behavior during fabrication and maturation, and sustaining the optimization of the process design accordingly [9]. Multi-component models can rely on diverse approaches on the broad spectrum between holistic, comprehensive modeling and hypothesis-driven modeling [49]. Future approaches shall find the right trade-off between these two, or sustain hybrid modeling, consistently combining model components based on different modeling strategies [50].

Multi-stage modeling: computational methods must comprise the multiple process stages composing a TERM biofabrication process [163, 164], drawing meaningful relations between them to support multi-stage modeling and optimization. In this perspective, computational models shall either model multiple stages together, or support the usage of hybrid models [50] that cover multiple stages by composition of multiple single-stage models.

Abstraction tuning: Computational methods must develop to sustain tunable abstraction in TERM biofabrication models. The abstraction of mechanistic models into behavioral models, while preserving good model prediction accuracy and explainability, is an established strategy to enhance computational feasibility of model-based DSE in other domains [165]. Future research shall implement the same principle to

sustain tunable abstraction in model-based DSE of TERM biofabrication processes.

Computational scale-up: Computational methods must enhance the feasibility of model-based DSE for TERM biofabrication, especially when dealing with large design spaces. Heuristic and meta-heuristic optimization strategies in model-based DSE can efficiently explore huge design spaces [43]. Novel computational methods shall implement and innovate such techniques towards a general increase in the exploration of large TERM biofabrication process design spaces.

These advances will make computational approaches the key for unlocking the potential of TERM biofabrication for faster clinical translation, targeting more complex applications and reaching improved clinical outcomes.

Funding acknowledgment

This study was carried out within the project “SAISEI - Multi-Scale Protocols Generation for Intelligent Biofabrication” funded by the Ministero dell’Università e della Ricerca (Italian Ministry for Universities and Research) – within the Progetti di Rilevante Interesse Nazionale (PRIN) 2022 program (D.D.104 -02/02/2022) [Prot. 20222RT5LC].

CRediT authorship contribution statement

Roberta Bardini: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Stefano Di Carlo:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [1] Groll J, Boland T, Blunk T, Burdick JA, Cho D-W, Dalton PD, et al. Biofabrication: reappraising the definition of an evolving field. *Biofabrication* 2016;8:013001.
- [2] Moroni L, Boland T, Burdick JA, De Maria C, Derby B, Forgacs G, et al. Biofabrication: a guide to technology and terminology. *Trends Biotechnol* 2018;36:384–402.
- [3] Raman R, Bashir R. Biomimicry, biofabrication, and biohybrid systems: the emergence and evolution of biological design. *Adv Healthc Mater* 2017;6:1700496.
- [4] Maartens JH, De-Juan-Pardo E, Wunner FM, Simula A, Voelcker NH, Barry SC, et al. Challenges and opportunities in the manufacture and expansion of cells for therapy. *Expert Opin Biol Ther* 2017;17:1221–33.
- [5] Sadowski MI, Grant C, Fell TS. Harnessing qbd, programming languages, and automation for reproducible biology. *Trends Biotechnol* 2016;34:214–27.
- [6] Castilho M, de Ruijter M, Beirne S, Villette CC, Ito K, Wallace GG, et al. Multitechnology biofabrication: a new approach for the manufacturing of functional tissue structures? *Trends Biotechnol* 2020;38:1316–28.
- [7] Neubauer P, Glauche F, Cruz-Bournazou MN. Bioprocess development in the era of digitalization. *Eng Life Sci* 2017;17:1140.
- [8] Kasemiire A, Avohou HT, De Bleye C, Sacre P-Y, Dumont E, Hubert P, et al. Design of experiments and design space approaches in the pharmaceutical bioprocess optimization. *Eur J Pharm Biopharm* 2021.
- [9] Lesage R, Kerkhofs J, Geris L. Computational modeling and reverse engineering to reveal dominant regulatory interactions controlling osteochondral differentiation: potential for regenerative medicine. *Front Bioeng Biotechnol* 2018;6:165.
- [10] Andréa Dornowsek Jd, Rezende RA, Lopes da Silva JV. The role of information technology in the future of 3d biofabrication. *J 3D Print Med* 2017;1:63–74.
- [11] Post JN, Loerakker S, Merks RM, Carlier A. Implementing computational modeling in tissue engineering: where disciplines meet. *Tissue Eng, Part A* 2022;28:542–54.
- [12] Donthu N, Kumar S, Mukherjee D, Pandey N, Lim WM. How to conduct a bibliometric analysis: an overview and guidelines. *J Bus Res* 2021;133:285–96.
- [13] Chen C. Science mapping: a systematic review of the literature. *J Data Inf Sci* 2017;2.
- [14] Perianes-Rodriguez A, Waltman L, Van Eck NJ. Constructing bibliometric networks: a comparison between full and fractional counting. *J Informetr* 2016;10:1178–95.
- [15] Van Eck NJ, Waltman L. Text mining and visualization using vosviewer. *arXiv preprint arXiv:1109.2058*, 2011.

- [16] National center for biotechnology information, 2022. URL: <https://pubmed.ncbi.nlm.nih.gov/>.
- [17] Chansoria P, Schuchard K, Shirwaiker RA. Process hybridization schemes for multiscale engineered tissue biofabrication. *WIREs Nanomed Nanobiotechnol* 2021;13:e1673.
- [18] Tellechea-Luzardo J, Otero-Muras I, Goñi-Moreno A, Carbonell P. Fast bio-foundries: coping with the challenges of biomanufacturing. *Trends Biotechnol* 2022.
- [19] Thornbury S. *AZ of ELT*. Macmillan Educ; 2006.
- [20] Hofmann P, Samp C, Urbach N. Robotic process automation. *EM* 2020;30:99–106.
- [21] Popkova EG, Ragulina YV, Bogoviz AV. Industry 4.0: industrial revolution of the 21st century. Springer; 2019.
- [22] Herwig C, Pörtner R, Möller J. Digital twins: applications to the design and optimization of bioprocesses, vol. 177. Springer Nature; 2021.
- [23] Zobel-Roos S, Schmidt A, Uhlenbrock L, Ditz R, Köster D, Strube J. Digital twins in biomanufacturing. In: *Digital twins*. Springer; 2020. p. 181–262.
- [24] Jones D, Snider C, Nassehi A, Yon J, Hicks B. Characterising the digital twin: a systematic literature review. *CIRP J Manuf Sci Technol* 2020;29:36–52.
- [25] Tellechea-Luzardo J, Winterhalter C, Wiedera P, Kozyra J, de Lorenzo V, Krasnogor N. Linking engineered cells to their digital twins: a version control system for strain engineering. *ACS Synth Biol* 2020;9:536–45.
- [26] Udugama IA, Lopez PC, Gargalo CL, Li X, Bayer C, Gernaey KV. Digital twin in biomanufacturing: challenges and opportunities towards its implementation. *Syst Microbiol Biomanuf* 2021;1–18.
- [27] Bayer B, Dalmau Diaz R, Melcher M, Striedner G, Duerkop M. Digital twin application for model-based doe to rapidly identify ideal process conditions for space-time yield optimization. *Processes* 2021;9:1109.
- [28] Geris L, Guyot Y, Schrooten J, Papantoniou I. In silico regenerative medicine: how computational tools allow regulatory and financial challenges to be addressed in a volatile market. *Interface Focus* 2016;6:20150105.
- [29] Geris L, Lambrechts T, Carlier A, Papantoniou I. The future is digital: in silico tissue engineering. *Curr Opin Biomed Eng* 2018;6:92–8.
- [30] Baker M. Reproducibility crisis. *Nature* 2016;533:353–66.
- [31] Marton RM, Ioannidis JP. A comprehensive analysis of protocols for deriving dopaminergic neurons from human pluripotent stem cells. *Stem Cells Transl Med* 2019;8:366–74.
- [32] Gilman J, Walls L, Bandiera L, Menolascina F. Statistical design of experiments for synthetic biology. *ACS Synth Biol* 2021;10:1–18.
- [33] Chang KH, Zandstra PW. Quantitative screening of embryonic stem cell differentiation: endoderm formation as a model. *Biotechnol Bioeng* 2004;88:287–98.
- [34] Walsh I, Myint M, Nguyen-Khuong T, Ho YS, Ng SK, Lakshmanan M. Harnessing the potential of machine learning for advancing “quality by design” in biomanufacturing. *Mabs*, vol. 14. Taylor & Francis; 2022. p. 2013593.
- [35] Jankovic A, Chaudhary G, Goia F. Designing the design of experiments (doe)—an investigation on the influence of different factorial designs on the characterization of complex systems. *Energy Build* 2021;250:111298.
- [36] Bukys MA, Mihas A, Finney K, Sears K, Trivedi D, Wang Y, et al. High-dimensional design-of-experiments extracts small-molecule-only induction conditions for dorsal pancreatic endoderm from pluripotency. *iScience* 2020;23:101346.
- [37] Kuterbekov M, Machillot P, Baillet F, Jonas AM, Glinel K, Picart C. Design of experiments to assess the effect of culture parameters on the osteogenic differentiation of human adipose stromal cells. *Stem Cell Res Ther* 2019;10:1–9.
- [38] Zhang S, Vijayavenkataraman S, Lu WF, Fuh JY. A review on the use of computational methods to characterize, design, and optimize tissue engineering scaffolds, with a potential in 3d printing fabrication. *J Biomed Mater Res, Part B, Appl Biomater* 2019;107:1329–51.
- [39] Jazdi N, Talkhestani BA, Maschler B, Weyrich M. Realization of ai-enhanced industrial automation systems using intelligent digital twins. *Proc CIRP* 2021;97:396–400.
- [40] Lyu G, Brennan RW. Towards iec 61499 based distributed intelligent automation: design and computing perspectives. 2019 IEEE 17th international conference on industrial informatics (INDIN), vol. 1. IEEE; 2019. p. 160–3.
- [41] Ng KK, Chen C-H, Lee CK, Jiao JR, Yang Z-X. A systematic literature review on intelligent automation: aligning concepts from theory, practice, and future perspectives. *Adv Eng Inform* 2021;47:101246.
- [42] Zhu X, Wang Z, Teng F. A review of regulated self-organizing approaches for tissue regeneration. *Prog Biophys Mol Biol* 2021;167:63–78.
- [43] do Amaral JVS, Montevecchi JAB, de Carvalho Miranda R, de Sousa Junior WT. Metamodel-based simulation optimization: a systematic literature review. *Simul Model Pract Theory* 2022;114:102403.
- [44] Flenner E, Janosi L, Barz B, Neagu A, Forgacs G, Kosztin I. Kinetic monte carlo and cellular particle dynamics simulations of multicellular systems. *Phys Rev E* 2012;85:031907.
- [45] Bardini R, Benso A, Politano G, Di Carlo S. Nets-within-nets for modeling emergent patterns in ontogenetic processes. *Comput Struct Biotechnol J* 2021;19:5701–21.
- [46] Bardini R, Di Carlo S, Politano G, Benso A. Modeling antibiotic resistance in the microbiota using multi-level petri nets. *BMC Syst Biol* 2018;12:59–79.
- [47] Gutenkunst RN, Waterfall JJ, Casey FP, Brown KS, Myers CR, Sethna JP. Universally sloppy parameter sensitivities in systems biology models. *PLoS Comput Biol* 2007;3:e189.
- [48] Eggert S, Hutmacher DW. In vitro disease models 4.0 via automation and high-throughput processing. *Biofabr* 2019;11:043002.
- [49] Eriksson O, Bhalla US, Blackwell KT, Crook SM, Keller D, Kramer A, et al. Combining hypothesis-and data-driven neuroscience modeling in fair workflows. *eLife* 2022;11:e69013.
- [50] Bardini R, Politano G, Benso A, Di Carlo S. Multi-level and hybrid modelling approaches for systems biology. *Comput Struct Biotechnol J* 2017;15:396–402.
- [51] Paim Á, Cardozo NS, Pranke P, Tessaro IC. Process system engineering methodologies applied to tissue development and regenerative medicine. *Cutting-edge enabling technologies for regenerative medicine*; 2018. p. 445–63.
- [52] Garcia L, Robinson-Ziegler R, Reiterer MW, Panoskaltis-Mortari A. Collaborative findings on manufacturing needs for biofabrication of engineered tissues and organs. *Regen Eng Transl Med* 2018;4:45–50.
- [53] Mustra M, Delac K, Grgic M. Overview of the dicom standard. 2008 50th international symposium ELMAR, vol. 1. IEEE; 2008. p. 39–44.
- [54] Marro A, Bandukwala T, Mak W. Three-dimensional printing and medical imaging: a review of the methods and applications. *Curr Probl Diagn Radiol* 2016;45:2–9.
- [55] Yu N, Nguyen T, Cho YD, Kavanagh NM, Ghassib I, Giannobile WV. Personalized scaffolding technologies for alveolar bone regenerative medicine. *Orthod Craniofac Res* 2019;22:69–75.
- [56] Park S-H, Kang B-K, Lee JE, Chun SW, Jang K, Kim YH, et al. Design and fabrication of a thin-walled free-form scaffold on the basis of medical image data and a 3d printed template: its potential use in bile duct regeneration. *ACS Appl Mater Interfaces* 2017;9:12290–8.
- [57] Vashistha R, Kumar P, Dangi AK, Sharma N, Chhabra D, Shukla P. Quest for cardiovascular interventions: precise modeling and 3d printing of heart valves. *J Biol Eng* 2019;13:1–12.
- [58] Kim J, McKee JA, Fontenot JJ, Jung JP. Engineering tissue fabrication with machine intelligence: generating a blueprint for regeneration. *Front Bioeng Biotechnol* 2020;7:443.
- [59] Kim J, Lee JK, Lee KM. Accurate image super-resolution using very deep convolutional networks. In: *Proceedings of the IEEE conference on computer vision and pattern recognition*; 2016. p. 1646–54.
- [60] Ng WL, Chan A, Ong YS, Chua CK. Deep learning for fabrication and maturation of 3d bioprinted tissues and organs. *Virtual Phys Prototyp* 2020;15:340–58.
- [61] Nagao Y, Sakamoto M, Chinen T, Okada Y, Takao D. Robust classification of cell cycle phase and biological feature extraction by image-based deep learning. *Mol Biol Cell* 2020;31:1346–54.
- [62] An J, Chua CK, Mironov V. Application of machine learning in 3d bioprinting: focus on development of big data and digital twin. *Int J Bioprint* 2021;7.
- [63] Mir TA, Iwanaga S, Kurooka T, Toda H, Sakai S, Nakamura M. Biofabrication offers future hope for tackling various obstacles and challenges in tissue engineering and regenerative medicine: a perspective. *Int J Bioprint* 2019;5.
- [64] Liu Y, Li X, Qu X, Zhu L, He J, Zhao Q, et al. The fabrication and cell culture of three-dimensional rolled scaffolds with complex micro-architectures. *Biofabr* 2012;4:015004.
- [65] Top N, Şahin İ, Gökçe H, Gökçe H. Computer-aided design and additive manufacturing of bone scaffolds for tissue engineering: state of the art. *J Mater Res* 2021;1–21.
- [66] Ozbolat IT, Koc B. Modeling of spatially controlled biomolecules in three-dimensional porous alginate structures. *J Med Devices* 2010;4:041003.
- [67] Bishop ES, Mostafa S, Pakvasa M, Luu HH, Lee MJ, Wolf JM, et al. 3-d bioprinting technologies in tissue engineering and regenerative medicine: current and future trends. *Genes Dis* 2017;4:185–95.
- [68] Egan PF, Gonella VC, Engelsperger M, Ferguson SJ, Shea K. Computationally designed lattices with tuned properties for tissue engineering using 3d printing. *PLoS ONE* 2017;12:e0182902.
- [69] Roque R, Barbosa GF, Guastaldi AC. Design and 3d bioprinting of interconnected porous scaffolds for bone regeneration. An additive manufacturing approach. *J Manuf Process* 2021;64:655–63.
- [70] Goh GD, Sing SL, Yeong WY. A review on machine learning in 3d printing: applications, potential, and challenges. *Artif Intell Rev* 2021;54:63–94.
- [71] Ali MH, Batai S, Sarbassov D. 3d printing: a critical review of current development and future prospects. *Rapid Prototyping J* 2019.
- [72] Menon A, Póczos B, Feinberg AW, Washburn NR. Optimization of silicone 3d printing with hierarchical machine learning, 3D. *Print Addit Manuf* 2019;6:181–9.
- [73] Kalyan MS, Kumar H, Nagdev L. Latest trends in additive manufacturing. *IOP conference series: materials science and engineering*, vol. 1. IOP Publishing; 2021. p. 012020.
- [74] Ahmed A, Arya S, Gupta V, Furukawa H, Khosla A. 4d printing: fundamentals, materials, applications and challenges. *Polymer* 2021;228:123926.
- [75] Metz C, Duda GN, Checa S. Towards multi-dynamic mechano-biological optimization of 3d-printed scaffolds to foster bone regeneration. *Acta Biomater* 2020;101:117–27.
- [76] Pakhomova C, Popov D, Maltsev E, Akhatov I, Pasko A. Software for bioprinting. *Int J Bioprint* 2020;6.
- [77] Neagu A. Role of computer simulation to predict the outcome of 3d bioprinting. *J 3D Print Med* 2017;1:103–21.
- [78] Emmert MY, Schmitt BA, Loerakker S, Sanders B, Priestersbach H, Fioretta ES, et al. Computational modeling guides tissue-engineered heart valve design for

- long-term in vivo performance in a translational sheep model. *Sci Transl Med* 2018;10:eaa4587.
- [79] Hsu M-C, Kamensky D, Xu F, Kiendl J, Wang C, Wu MC, et al. Dynamic and fluid–structure interaction simulations of bioprosthetic heart valves using parametric design with t-splines and fung-type material models. *Comput Mech* 2015;55:1211–25.
- [80] Dellaquila A, Campodoni E, Tampieri A, Sandri M. Overcoming the design challenge in 3d biomimetic hybrid scaffolds for bone and osteochondral regeneration by factorial design. *Front Bioeng Biotechnol* 2020;8:743.
- [81] Shi M, Hilton HH. Rational integrated modeling and analyses of system engineered linear viscoelastic 3-d/4-d printing protocols and their topology optimization. In: *AIAA scitech* 2021 forum; 2021. p. 0701.
- [82] Chai YC, Carlier A, Bolander J, Roberts SJ, Geris L, Schrooten J, et al. Current views on calcium phosphate osteogenicity and the translation into effective bone regeneration strategies. *Acta Biomater* 2012;8:3876–87.
- [83] Lin CY, Kikuchi N, Hollister SJ. A novel method for biomaterial scaffold internal architecture design to match bone elastic properties with desired porosity. *J Biomech* 2004;37:623–36.
- [84] Manzano S, Poveda-Reyes S, Ferrer GG, Ochoa I, Doweidar MH. Computational analysis of cartilage implants based on an interpenetrated polymer network for tissue repairing. *Comput Methods Programs Biomed* 2014;116:249–59.
- [85] Coelho PG, Hollister SJ, Flanagan CL, Fernandes PR. Bioresorbable scaffolds for bone tissue engineering: optimal design, fabrication, mechanical testing and scale-size effects analysis. *Med Eng Phys* 2015;37:287–96.
- [86] Williams JM, Adewunmi A, Schek RM, Flanagan CL, Krebsbach PH, Feinberg SE, et al. Bone tissue engineering using polycaprolactone scaffolds fabricated via selective laser sintering. *Biomaterials* 2005;26:4817–27.
- [87] Krishna LSR, Mahesh N, Sateesh N. Topology optimization using solid isotropic material with penalization technique for additive manufacturing. *Mater Today Proc* 2017;4:1414–22.
- [88] Tang Y, Kurtz A, Zhao YF. Bidirectional evolutionary structural optimization (beso) based design method for lattice structure to be fabricated by additive manufacturing. *Comput Aided Des* 2015;69:91–101.
- [89] Wang Y, Gao J, Luo Z, Brown T, Zhang N. Level-set topology optimization for multimaterial and multifunctional mechanical metamaterials. *Eng Optim* 2017;49:22–42.
- [90] Zolfagharian A, Denk M, Kouzani AZ, Bodaghi M, Nahavandi S, Kaynak A. Effects of topology optimization in multimaterial 3d bioprinting of soft actuators. *Int J Bioprint* 2020;6.
- [91] Vijayavenkataraman S, Zhang L, Zhang S, Hsi Fuh JY, Lu WF. Triply periodic minimal surfaces sheet scaffolds for tissue engineering applications: an optimization approach toward biomimetic scaffold design. *ACS Appl Bio Mater* 2018;1:259–69.
- [92] Khoda A, Ozbolat IT, Koc B. A functionally gradient variational porosity architecture for hollowed scaffolds fabrication. *Biofabr* 2011;3:034106.
- [93] Khoda A, Ozbolat IT, Koc B. Designing heterogeneous porous tissue scaffolds for additive manufacturing processes. *Comput Aided Des* 2013;45:1507–23.
- [94] Khoda A, Ozbolat IT, Koc B. Engineered tissue scaffolds with variational porous architecture. *J Biomech Eng* 2011;133.
- [95] Bidan CM, Kommareddy KP, Rumpel M, Kollmannsberger P, Fratzl P, Dunlop JW. Geometry as a factor for tissue growth: towards shape optimization of tissue engineering scaffolds. *Adv Healthc Mater* 2013;2:186–94.
- [96] Wu C, Fang J, Entezari A, Sun G, Swain MV, Xu Y, et al. A time-dependent mechanobiology-based topology optimization to enhance bone growth in tissue scaffolds. *J Biomech* 2021;117:110233.
- [97] Chang C-C, Chen Y, Zhou S, Mai Y-W, Li Q. Computational design for scaffold tissue engineering. In: *Biomaterials for implants and scaffolds*. Springer; 2017. p. 349–69.
- [98] Yilin G, Fuh Ying Hsi J, Wen Feng L. Multiscale topology optimisation with non-parametric microstructures using three-dimensional convolutional neural network (3d-cnn) models. *Virtual Phys Prototyp* 2021;1–12.
- [99] Hulsman M, Hulshof F, Unadkat H, Papenburg BJ, Stamatis DF, Truckenmüller R, et al. Analysis of high-throughput screening reveals the effect of surface topographies on cellular morphology. *Acta Biomater* 2015;15:29–38.
- [100] Mc Donnell P, Harrison N, Liebschner M, Mc Hugh P. Simulation of vertebral trabecular bone loss using voxel finite element analysis. *J Biomech* 2009;42:2789–96.
- [101] Iori G, Peralta L, Reisinger A, Heyer F, Wyers C, van den Bergh J, et al. Femur strength predictions by nonlinear homogenized voxel finite element models reflect the microarchitecture of the femoral neck. *Med Eng Phys* 2020;79:60–6.
- [102] Mishra RN, Singh MK, Kumar V. Biomechanical analysis of human femur using finite element method: a review study. *Mater Today Proc* 2022.
- [103] Ramu M, Ananthasubramanian M, Kumaresan T, Gandhinathan R, Jothi S. Optimization of the configuration of porous bone scaffolds made of polyamide/hydroxyapatite composites using selective laser sintering for tissue engineering applications. *Bio-Med Mater Eng* 2018;29:739–55.
- [104] Zheng L, Yang J, Hu X, Luo J. Three dimensional finite element analysis of a novel osteointegrated dental implant designed to reduce stress peak of cortical bone. *Acta Bioeng Biomech* 2014;16.
- [105] Hendrikson W, van Blitterswijk C, Rouwkema J, Moroni L, et al. The use of finite element analyses to design and fabricate three-dimensional scaffolds for skeletal tissue engineering. *Front Bioeng Biotechnol* 2017;5:30.
- [106] Boccaccio A, Fiorentino M, Gattullo M, Manghisi V, Monno G, Uva A. Geometry modelling of regular scaffolds for bone tissue engineering: a computational mechanobiological approach. In: *Advances on mechanics, design engineering and manufacturing II*. Springer; 2019. p. 517–26.
- [107] Landge AN, Jordan BM, Diego X, Müller P. Pattern formation mechanisms of self-organizing reaction-diffusion systems. *Dev Biol* 2020;460:2–11.
- [108] Velasco MA, Lancheros Y, Garzón-Alvarado DA. Geometric and mechanical properties evaluation of scaffolds for bone tissue applications designing by a reaction-diffusion models and manufactured with a material jetting system. *J Comput Des Eng* 2016;3:385–97.
- [109] Dorsey PJ, Scalise D, Schulman R. A model of spatio-temporal regulation within biomaterials using dna reaction–diffusion waveguides. *R Soc Open Sci* 2022;9:220200.
- [110] Adachi T, Osako Y, Tanaka M, Hojo M, Hollister SJ. Framework for optimal design of porous scaffold microstructure by computational simulation of bone regeneration. *Biomaterials* 2006;27:3964–72.
- [111] Carlier A, Chai YC, Moesen M, Theys T, Schrooten J, Van Oosterwyck H, et al. Designing optimal calcium phosphate scaffold–cell combinations using an integrative model-based approach. *Acta Biomater* 2011;7:3573–85.
- [112] Koh Y-G, Lee J-A, Kim YS, Lee HY, Kim HJ, Kang K-T. Optimal mechanical properties of a scaffold for cartilage regeneration using finite element analysis. *J Tissue Eng* 2019;10:2041731419832133.
- [113] Tajsoleiman T, Abdekhodaie MJ, Gernaey KV, Krühne U. Efficient computational design of a scaffold for cartilage cell regeneration. *Bioeng* 2018;5:33.
- [114] Weber M-C, Fischer L, Damerau A, Ponomarev I, Pfeiffenberger M, Gaber T, et al. Macroscale mesenchymal condensation to study cytokine-driven cellular and matrix-related changes during cartilage degradation. *Biofabr* 2020;12:045016.
- [115] Loerakker S, Ristori T. Computational modeling for cardiovascular tissue engineering: the importance of including cell behavior in growth and remodeling algorithms. *Curr Opin Biomed Eng* 2020;15:1–9.
- [116] Szafron JM, Ramachandra AB, Breuer CK, Marsden AL, Humphrey JD. Optimization of tissue-engineered vascular graft design using computational modeling. *Tissue Eng Part C, Methods* 2019;25:561–70.
- [117] Bersini S, Gilardi M, Arrigoni C, Talò G, Zamai M, Zagra L, et al. Human in vitro 3d co-culture model to engineer vascularized bone-mimicking tissues combining computational tools and statistical experimental approach. *Biomaterials* 2016;76:157–72.
- [118] Wang J, Huang D, Yu H, Cheng Y, Ren H, Zhao Y. Developing tissue engineering strategies for liver regeneration. *Eng Regen* 2022;3:80–91.
- [119] Teng C-L, Chen J-Y, Chang T-L, Hsiao S-K, Hsieh Y-K, Gorday KV, et al. Design of photocurable, biodegradable scaffolds for liver lobule regeneration via digital light process-additive manufacturing. *Biofabr* 2020;12:035024.
- [120] Borenstein JT, Weinberg EJ, Orrick BK, Sundback C, Kaazempur-Mofrad MR, Vacanti JP. Microfabrication of three-dimensional engineered scaffolds. *Tissue Eng* 2007;13:1837–44.
- [121] Hoganson DM, Pryor HI, Spool ID, Burns OH, Gilmore JR, Vacanti JP. Principles of biomimetic vascular network design applied to a tissue-engineered liver scaffold. *Tissue Eng, Part A* 2010;16:1469–77.
- [122] Ozbolat IT, Koc B. Multi-function based modeling of 3d heterogeneous wound scaffolds for improved wound healing. *Comput-Aided Des Appl* 2011;8:43–57.
- [123] Chiono V, Tonda-Turo C. Trends in the design of nerve guidance channels in peripheral nerve tissue engineering. *Prog Neurobiol* 2015;131:87–104.
- [124] Cidonio G, Glinka M, Dawson J, Oreffo R. The cell in the ink: improving bio-fabrication by printing stem cells for skeletal regenerative medicine. *Biomaterials* 2019;209:10–24.
- [125] Bahraminasab M, Edwards KL. Computational tailoring of orthopaedic biomaterials: design principles and aiding tools. In: *Biomaterials in orthopaedics and bone regeneration*. Springer; 2019. p. 15–31.
- [126] Uth N, Mueller J, Smucker B, Yousefi A-M. Validation of scaffold design optimization in bone tissue engineering: finite element modeling versus designed experiments. *Biofabr* 2017;9:015023.
- [127] Demirci N, Tönük E. Non-integer viscoelastic constitutive law to model soft biological tissues to in-vivo indentation. *Acta Bioeng Biomech* 2014;16.
- [128] Nazouri M, Seifzadeh A, Masaeli E. Characterization of polyvinyl alcohol hydrogels as tissue-engineered cartilage scaffolds using a coupled finite element-optimization algorithm. *J Biomech* 2020;99:109525.
- [129] Bas O, Lucarotti S, Angella DD, Castro NJ, Meinert C, Wunner FM, et al. Rational design and fabrication of multiphasic soft network composites for tissue engineering articular cartilage: a numerical model-based approach. *Chem Eng J* 2018;340:15–23.
- [130] Rackham OJ, Firas J, Fang H, Oates ME, Holmes ML, Knaupp AS, et al. A predictive computational framework for direct reprogramming between human cell types. *Nat Genet* 2016;48:331.
- [131] Jung S, Appleton E, Ali M, Church GM, Del Sol A. A computer-guided design tool to increase the efficiency of cellular conversions. *Nat Commun* 2021;12:1–12.
- [132] Lopa S, Piraino F, Talò G, Mainardi VL, Bersini S, Pierrro M, et al. Microfluidic biofabrication of 3d multicellular spheroids by modulation of non-geometrical parameters. *Front Bioeng Biotechnol* 2020;8:366.
- [133] Guillemot F, Mironov V, Nakamura M. Bioprinting is coming of age: report from the international conference on bioprinting and biofabrication in bordeaux (3b'09). *Biofabr* 2010;2:010201.

- [134] Reid JA, Mollica PA, Johnson GD, Ogle RC, Bruno RD, Sachs PC. Accessible bioprinting: adaptation of a low-cost 3d-printer for precise cell placement and stem cell differentiation. *Biofabr* 2016;8:025017.
- [135] Sheoran AJ, Kumar H. Fused deposition modeling process parameters optimization and effect on mechanical properties and part quality: review and reflection on present research. *Mater Today Proc* 2020;21:1659–72.
- [136] Buj-Corral I, Bagheri A, Sivatte-Adroer M. Effect of printing parameters on dimensional error, surface roughness and porosity of fff printed parts with grid structure. *Polymers* 2021;13:1213.
- [137] Aguilar IN, Smith LJ, Olivios III DJ, Chu T-MG, Kacena MA, Wagner DR. Scaffold-free bioprinting of mesenchymal stem cells with the regenova printer: optimization of printing parameters. *Bioprint* 2019;15:e00048.
- [138] Shi J, Song J, Song B, Lu WF. Multi-objective optimization design through machine learning for drop-on-demand bioprinting. *Engineering* 2019;5:586–93.
- [139] Shi J, Wu B, Song B, Song J, Li S, Trau D, et al. Learning-based cell injection control for precise drop-on-demand cell printing. *Ann Biomed Eng* 2018;46:1267–79.
- [140] Jin Z, Zhang Z, Shao X, Gu GX. Monitoring anomalies in 3d bioprinting with deep neural networks. *ACS Biomater Sci Eng* 2021.
- [141] Mukherjee S, Kumar JP. Application of an mcdm tool for selection of 3d bioprinting processes. In: *Innovative product design and intelligent manufacturing systems*. Springer; 2020. p. 787–97.
- [142] Silva C, Cortés-Rodríguez CJ, Hazur J, Reakasame S, Boccaccini AR. Rational design of a triple-layered coaxial extruder system: in silico and in vitro evaluations directed toward optimizing cell viability. *Int J Bioprint* 2020;6.
- [143] Nasrollahzadeh N, Applegate LA, Pioletti DP. Development of an effective cell seeding technique: simulation, implementation, and analysis of contributing factors, tissue engineering part C. *Methods* 2017;23:485–96.
- [144] Olivares AL, Lacroix D. Simulation of cell seeding within a three-dimensional porous scaffold: a fluid-particle analysis. *Tissue Eng Part C, Methods* 2012;18:624–31.
- [145] Sego T, Kasacheuski U, Hauersperger D, Tovar A, Moldovan NI. A heuristic computational model of basic cellular processes and oxygenation during spheroid-dependent biofabrication. *Biofabr* 2017;9:024104.
- [146] Burova I, Wall I, Shipley RJ. Mathematical and computational models for bone tissue engineering in bioreactor systems. *J Tissue Eng* 2019;10:2041731419827922.
- [147] Dattatreya M, Tiwari AK, Ghoshal B, Singh J. Predicting bone modeling parameters in response to mechanical loading. *IEEE Access* 2019;7:122561–72.
- [148] Vetsch JR, Betts DC, Müller R, Hofmann S. Flow velocity-driven differentiation of human mesenchymal stromal cells in silk fibroin scaffolds: a combined experimental and computational approach. *PLoS ONE* 2017;12:e0180781.
- [149] Robu A, Robu N, Neagu A. New software tools for hydrogel-based bioprinting. In: *2018 IEEE 12th international symposium on applied computational intelligence and informatics (SACI)*. IEEE; 2018. p. 1–5.
- [150] Santoro R, Olivares AL, Brans G, Wirz D, Longinotti C, Lacroix D, et al. Bioreactor based engineering of large-scale human cartilage grafts for joint resurfacing. *Biomaterials* 2010;31:8946–52.
- [151] Nguyen T, Carpentier O, Monchau F, Chai F, Hornez J-C, Hivart P. Numerical optimization of cell colonization modelling inside scaffold for perfusion bioreactor: a multiscale model. *Med Eng Phys* 2018;57:40–50.
- [152] Mehrian M, Geris L. Optimizing neotissue growth inside perfusion bioreactors with respect to culture and labor cost: a multi-objective optimization study using evolutionary algorithms. *Comput Methods Biomech Biomed Eng* 2020;23:285–94.
- [153] Giannantonio L, Bardini R, Di Carlo S. A methodology for co-simulation-based optimization of biofabrication protocols. In: *Bioinformatics and biomedical engineering: 9th international work-conference, IWBBIO 2022, maspalomas, Gran Canaria. Proceedings, part II*. Springer Nature; 2022. p. 179–92.
- [154] Conrardin R, Coreixas C, Latt J, Chopard B. Palacell2d: a framework for detailed tissue morphogenesis. *J Comput Sci* 2021;53:101353.
- [155] Castrignanò A, Bardini R, Savino A, Di Carlo S. A deep reinforcement learning approach to the optimization of epithelial sheets biofabrication. 2023. *bioRxiv* 2023–04.
- [156] Goble C, Cohen-Boulakia S, Soiland-Reyes S, Garijo D, Gil Y, Crusoe MR, et al. Fair computational workflows. *Data Intell* 2020;2:108–21.
- [157] Moreau D, Wiebels K, Boettiger C. Containers for computational reproducibility. *Nat Rev Methods Prim* 2023;3:50.
- [158] Steinman DA, Pereira VM. How patient specific are patient-specific computational models of cerebral aneurysms? An overview of sources of error and variability. *Neurosurg Focus* 2019;47:E14.
- [159] Gray RA, Pathmanathan P. Patient-specific cardiovascular computational modeling: diversity of personalization and challenges. *J Cardiovasc Transl Res* 2018;11:80–8.
- [160] Semple JL, Woolridge N, Lumsden CJ. In vitro, in vivo, in silico: computational systems in tissue engineering and regenerative medicine. *Tissue Eng* 2005;11:341–56.
- [161] Hogle LF. Intersections of technological and regulatory zones in regenerative medicine. *Global perspectives on stem cell technologies*; 2018. p. 51–84.
- [162] Umemura M, Morrison M. Comparative lessons in regenerative medicine readiness: learning from the uk and japanese experience. *Regen Med* 2021;16:269–82.
- [163] Urbani L, Camilli C, Phylactopoulos D-E, Crowley C, Natarajan D, Scottoni F, et al. Multi-stage bioengineering of a layered oesophagus with in vitro expanded muscle and epithelial adult progenitors. *Nat Commun* 2018;9:4286.
- [164] Karakya E, Fischer L, Hazur J, Boccaccini AR, Thievensen I, Detsch R. Strategies to evaluate alginate based bioinks applying extrusion printing for biofabrication. *Trans Addit Manuf Meets Med* 2020;2.
- [165] Schafer BC, Wang Z. High-level synthesis design space exploration: past, present, and future. *IEEE Trans Comput-Aided Des Integr Circuits Syst* 2019;39:2628–39.



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