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Simulation Analyses Related to Human Bone Scaffold: Utilisation of Solidworks® Software in 3D Modelling and Mechanical Simulation Analyses

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Abstract:
Bone loss is risen due to fractures, surgeries and traumatic injuries. Scientists and engineers work over the years to find solutions to heal and accelerate bone regeneration. Bone grafting technique has been utilised which projects significant improvement in bone regeneration area. An extensive study is essential on the relation between the mechanical properties of bone scaffolds and the design of bone scaffolds in forecasting permeability access to promote bone growth and nutrient distribution. In reducing cost and time, mechanical simulation analyses are beneficial to simulate the relation. There are abundant of review works on the mechanical simulation analyses towards orthopaedic metallic implants. While the review on simulation analyses towards bone scaffolds are scarce. Therefore, this review study is intended to expose the utilisation of computer simulation analysis, specifically Solidworks® software in modelling three-dimensional (3D) scaffold models, performing mechanical simulation and analysing bone scaffold structure. The data were collected from three main sources of Google search, Scopus search and Science Direct search. From this review procedure, there are various computational software have been combined and used to perform several types of simulation analyses on bone scaffolds including Solidwork, Ansys, Abaqus, COMSOL Multiphysics, MATLAB etc. Among the simulation analyses, two main tests that can be simulated are mechanical test and fluid modelling. Solidwork® as one of the computer-aided design softwares has been extensively used to design two and 3D models. The advancement of this software on the performance of mechanical simulation analyses has also extended its application towards variety of applications including on bone scaffold evaluation. There are several parameters which are necessary to be set prior to the conduction of mechanical simulation analysis such as applied forces, material properties, mesh properties and boundary condition. As a conclusion, Solidwork® software is applicable to be used as a 3D modelling software to design bone scaffolds and to perform mechanical simulation analyses.

Keywords: Mechanical simulation; 3D modelling; Assistive scaffold; Solidwork

1. Introduction

Grafting is a surgical technique that is used to replace and substitute missing bones to avoid highly complicated bone fractures that could present a severe risk to the patient's health [1]. Bone grafts are commonly used to treat various conditions, including delayed fracture union, non-congenital pseudoarthrosis, trauma, cancer and osseous tumour defects [1]. Bone grafts usage is the norm for treating skeletal fractures or restoring and regenerating missing bone, as demonstrated by the vast number of bone grafting procedures carried out around the world [2]. There are three primary methods to produce bone grafts: autographs, allografts and xenografts [2]. Autogenous, also known as autograft, is a grafting technique where the replacement bones are extracted from the patient's body and sometimes extracted from the iliac bone. While allograft is a grafting technique where the replacement bones are obtained from a bone bank or provided by a donor, on the other hand, xenograft is a grafting technique where bones are harvested from an animal or synthetic material such as hydroxyapatite (HA) or other biocompatible and naturally occurring substances with identical properties to the human bone [1]. Bone graft's design is often varied according to their form of structure which correspond to intended applications.

The rigidity and strength of scaffolds are crucial in managing maladjusted stress concentration and reducing stress shielding. Simultaneously, sufficient porosity and permeability are essential to promote bone growth and nutrient distribution based on biological activities [3]. The geometry architecture of scaffold to replace human trabecular bone needs to withstand static and dynamic loads, up to 20 MPa [4]. It should also compose of macro and micropores to promote cell growth and mineral precipitation, while nutrient and oxygen diffusion should interconnect all pores [4]. Arjunan *et al.* [3] have proposed various cellular and structural properties of scaffolds in an anatomically form [3]. The mechanical output of the scaffold was within reasonable range for the porous architecture. Therefore, it has therefore been understood that at a design stage, the permeability of scaffolds must be considered in conjunction with stiffness and strength to complement both the host bone's mechanical and biological healing capabilities [3].

Computational biomaterial simulations have recently gained considerable attention with the ability to deliver immediate results as an alternative and economical approach compared with experimental analysis. Numerous computational fluid dynamics (CFD) analyses have been conducted to evaluate the permeability and wall shear stress (WSS) of different types of scaffolds [5]. Through a combination of simulation and experiment, Arjunan *et al.* [3] compared the mechanical outputs of several design models. In their analysis, multiple mathematical models with significant determination coefficients have estimated the length, porosity and elastic modulus of the alpha-beta titanium alloy (Ti6Al4V)-based cellular structures. Finite element analysis (FEA) also has been used to model stress-strain data through simulated compression analysis [6]. The analysis can be carried out on all structures, to obtain efficient numerical simulations with precise results of finite elements to avoid singularities on the numerical models and to avoid additional computational time [6]. Thus, computerised simulation becomes a common engineering practice for model evaluation.

Solidworks® is a computer-aided software (CAD) that can be used to create new designs, models and structures. It provides scratch architecture, where both three-dimensional (3D) and two-dimensional (2D) architectures can be constructed [7]. The combination of modelling and FEA allows the simulated investigation of mechanical and biological behaviours on patient-specific implants at a reduced cost. The first step in simulation has been set to determine the physical problem of design models. The limiting conditions, components materials and the characteristics of each substance are the critical criteria that should be defined [8]. Previously, there are abundant of review works on the mechanical simulation analyses towards orthopaedic metallic implants. While the review on simulation analyses towards bone scaffolds are scarce. Those information, provided in this review study is aimed to expose the utilisation of computer simulation analysis, specifically Solidworks® software in modelling three-dimensional (3D) bone scaffolds and analysing the bone scaffold structure. The review starts with the overview of bone tissue engineering, followed by the common performed simulation analyses in bone implantation area. Then, specific simulation softwares for bone scaffold evaluation are discussed by highlighting the utilisation of Solidworks® software. The data were collected from three main sources of Google search, Scopus search and Science Direct search.

2. Bone Tissue Engineering

Bone grafts and metallic prosthetic implants are the recent approaches used to increase and stimulate new bone formation to replace and regenerate bone deficiencies [9]. However, the transplantation of extensively used biomaterials in dentistry needs diagnosis under specific clinical presentations [10]. According to Hung [1], the first bone implant recorded was implemented in 1668, and by the year 2001, bone grafting procedures have reached 500,000 in the United States of America (USA) and 2 million worldwide. Bone grafting materials should be ideal and meet precise specification such as being bioresorbable, osteoconductive, biocompatible, osteoinductive, porous, structurally similar to bone, mechanically resistant, easy to use, safe and cost-effective [11, 12].

The actual structure of bone tissues is a kind of complex porous construction with irregular pore structure and uneven distribution of pores and porosity. The scaffold should be porous, as the supporting structure for cell growth Smooth surface structure without distortion or sharp edges, is preferred to facilitate the attachment and proliferation of scaffolding cells. Furthermore, bone tissue porous scaffolds also play an important role in the transport of nutrients and in the removal of waste during cell growth [12]. The concept of using scaffolds in bone tissue engineering is a key factor in the regeneration of bone defects of critical size [12]. Cells should attach on the embedded scaffolds and expand on the porous surfaces. The structural morphology and mechanical resistance are provided by the scaffold surface, on which the adhering cells can grow [13].

According to Arjunan *et al.* [3], critically engineered rigidity and strength of a scaffold are important for handling maladjusted stress accumulation and reducing stress shielding. At the same time, sufficient porosity and permeability are essential to promote biological processes associated with bone growth and nutrient distribution. To produce an efficient bone scaffold, a rigorous combination of all these parameters is important. A porosity and pore size of 70 – 90% and 450 - 700 μm respectively, are typically suggested as appropriate parameters for approaching human bone properties [3]. Models of different shapes, different porosities and different pore sizes can be obtained by changing function parameters, which offers a great possibility in fitting the human bone tissue structure [12].

3. Simulation Analyses in Bone Implantation

The simulation for modelling of food, pharmaceutical, biochemical and other chemical sectors established in the early nineties because these processes are complex, and it was not easy to be simulated [14]. They mentioned that the Monte Carlo simulation which is an excellent method to assess the impact on the operation spread of economic performance was used to quantify the risk of development process where they also used this method in their study to perform the manufacturing process of techno-economic analysis for nanotubes made of chitosan–titanium dioxide (TiO_2) [14]. In bone implantation, there are three main area that have been explored with the conduction of simulation analyses including bone implant, bone scaffold and bone cement.

3.1 Bone implant

In the area of implant reconstruction, there are researchers who investigated the effects of micro thread on stress distribution during bone pre-implantation using FEA. Different types of bones were constructed using several computational models of the human mandible with the simulation of bone resorption [15]. A healthy male mandibular bone was scanned using a cone-beam computed tomography where the acquired images were imported to Materialise-Mimics v17 software for further image processing and modelling. Finally, the model was tested with Abaqus 2016, Dassault Systems. On a parallel study, other researchers evaluated the influence of bone types in terms of bone density on generated stress distribution [16]. They used numerical simulation techniques using Abaqus statistical package software.

3.2 Bone scaffold

The strength and the stiffness of bone scaffolds are essential for stress management. In bone scaffolds, the balance between porosity, permeability and mechanical properties are the keys to facilitate biological activities that associated with bone growth and nutrient delivery [3]. The investigation on the relationship between strength, stiffness, permeability and stress along with porosity was done using Darcy’s law through a permeability test using Ansys Fluent CFD solver. Another experimental test using Ashby’s criterion and finite element method (FEM) were also conducted for the determination of mechanical properties using Ansys non-linear mechanical solver. In the study of gyroid structures with different volumes fraction which was conducted by Ma *et al*. [17], the parts were modelled and tested using different software’s where PTC Creo 3.0 was used to create 3D models, Mimics 17.0 software was used to rebuild the 3D models obtained from CT scans and ImageJ software was used to analyse the surface appearance and the section thickness at different heights.

3.3 Bone cement

Herrera *et al.* [18] found that during five years experimental analysis, a periprosthetic bone remodelling, associated with ABG-II (Stryker) and Versys (Zimmer) cemented stem models were implanted in old patients, randomly. This study was conducted as a clinical study using finite element simulation to investigate biomedical changes due to hip arthroplasty. The cancellous bone geometry was determined using CT scans of the patient's femur and the obtained images were meshed using I-Deas software. The calculations of the analysis were conducted using Abaqus 6.10 software.

According to Giner *et al*. [19], the estimation of cement line's critical energy in cortical bone tissues was proposed. The analysis method was conducted using correlating experimental tests and finite element simulation due to the difficulty in using experimental method. Three points bending test of ovine bone and both initial and growth of microcracks simulated using finite element in damage models were simulated based on a maximum principal strain criterion. Plot Digitizer was used to define the micro samples' outer boundaries and the contours of the osteons. The Abaqus software was then used to generate the Spline and transferred into Python as a script for simulation.

4. Simulation Software for Bone Scaffold Evaluation

Lots of software are being used for the simulation of biomedical applications, especially for bone application design and validation. The computational methods and software simulation have been extensively used as the mechanical testing on scaffolds in forecasting cell proliferation, oxygen consumption and scaffold degradation [20]. Abaqus software, created by Dassault Systems, is used as a software for analysis based on FEM technique. As an example, the modulation and the simulation of referenced lattice were conducted using Abaqus software [21]. The hollow cube and the truncated hexahedron cell have been tested to predict the behaviour of those unit cells under compression test using Abaqus 6.14 FEA package [21]. COMSOL Multiphysics is a metaphysical simulation software that is used for modelling devices, designs and processes in various engineering disciplines. This software can understand, optimise and even predict physics-based processes through numerical solutions (COMSOL website). In the study conducted by Arjunan *et al.* [3], the numerical analysis on biomaterial Ti6Al4V-based scaffolds was done by using COMSOL Multiphysics through the simulation of compression stress-strain tests.

According to Yusop *et al.* [22], the degradation behaviour of Cur-Fe and 80C-20P-Fe scaffolds was evaluated and compared using COMSOL Multiphysics software and MATLAB. Another software that is used for research is K3DSurf, a program that is used to visualise mathematical models in three to six dimensions using parametric equations. Based on the study by Ali *et al.* [5], the evaluation on eight different bone scaffolds models was done by investigating the flow of fluids within the scaffolds using CFD which is a software that simulates the motion of fluids while K3DSurf was used for visualising the exported parametric equations.

5. SOLIDWORKS

Solidworks® is a parametric modeler that uses dimensions, parameters and relationships to define 3D shapes [23]. It was first introduced in 1995 and becomes one of the leading softwares in 3D modelling and analysis [23]. The improvements and the expansion of this software application has expanded its applications to various industries and research institutes which use this software in designing, modelling and simulating stable structures [24]. The software allows engineers and designers to create mathematically solid models and by assigning the desired material properties, it allows them to simulate and evaluate the behaviour of the designed part using FEM [24]. This software has a wide range of applications such as simulation, motion, flow simulation and many others [25].

Figure 1 shows the utilisation of Solidworks® in designing bone scaffold. Researchers have explored various types of pore structure and pore dimension for bone scaffold development [20]. The diversity of pore structure is essential to allow fluid permeability for cell integration within bone scaffolds. However, greater pore structure will compensate the mechanical integrity of the scaffolds, thus inducing the degradation properties and disturb the scaffold stability. Fast degradation and low mechanical integrity are always directing towards implantation and treatment failures.

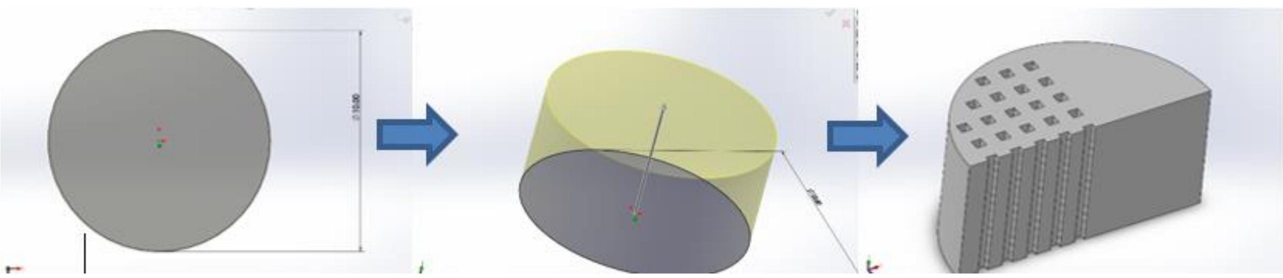

Figure 1. Bone scaffold design using Solidworks®

Table 1 lists several previous research which utilised Solidwork® in designing 3D model of bone scaffolds. Pore shapes that approaching a circular shape is concluded to distribute applied stress homogenously with better anisotropic properties compared to edges pore shapes.

Table 1. Previous research on Solidwork® utilisation in designing 3D model of bone scaffolds

Design variation	**Porosity**	**Findings**	**Author, Year**	**Reference**
Circle and square pore designs with size ranged from 1 mm to 2 mm	80%	The circle pore design distributed the stress homogenously compared to the square pore design which produced concentrated stress due to sharp edges, thus lowering the elastic modulus.	Tang *et al.*, 2020	[26]
Plate-like design with 0.5 mm pore size and sphere-shaped design with 1.0 mm pore size	86%	Greater Young's modulus and permeability on the plate-like design compared to the sphere-shaped design.	Kadir Hussein *et al.*, 2021	[27]
Cubic, triangular and hexagonal polyhedral unit cells with 120, 340 and 600 µm pore size	Up to 70%	The hexagonal polyhedral unit cells are categorised as anisotropic structure which beneficial for osteoconductivity while another two designs are considered isotropic.	Lipowiecki and Brabazon, 2009	[28]
Cylindrical scaffold with 20 mm diameter and 400 µm pore size	-	The addition of HA particles increased the compressive strength and Young's modulus of printed polymer scaffolds.	Rezania *et al.*, 2022	[29]
Triply periodic minimal surface scaffolds pore diameters with 314, 354, 394 and 434 µm pore sizes	51.7% - 68.8%	The inlet velocity and mass flow reduced with the increment of pore size.	Wang *et al.*, 2019	[30]

5.1 Types of analyses

Zhao *et al*. [31] conducted a study on different design of bone scaffolds in which the scaffolds were designed using Solidworks® and fabricated by selected laser melting machine. In that study, the mechanical properties of these bone scaffolds were tested using FEM by utilising similar software. The FEM can be used to accurately predict the behaviour of whole bone by setting the applied forces, its magnitude and the applied direction.

A study of heat transfer in hip replacements made of bone cement was performed by Ikekwem *et al.* [32], which used Solidworks® simulation software to perform steady-state thermal analysis on 3D structures. The authors found that poly(methyl methacrylate) (PMMA) resulted in a heat raise for the whole assembly hip replacement system and also created a heat flux [32].

Solidworks® has also been used to create closed-cell honeycomb Nitinol stent to evaluate the sealing stress, crimping strain and contact forces [33]. Dacron was designed to cover or coat the Nitinol stent, followed by the simulation analyses using FEM method [33]. Besides, Solidworks® that is integrated with other software such as MATLAB is capable to conduct various studies to enhance performance outputs [34]. Both softwares have been used to develop a framework for automatic optimisation, aiming to reduce the stress transcatheter aortic valve (TAV) leaflets through the projection of Von Misses stresses contours [34].

5.2 Analysis parameters

There are several parameters which are necessary to be declared for the conduction of simulation analysis using Solidworks® including the applied forces, material properties, mesh properties and boundary condition [35]. The applied loading is critically set to imitate the forces acting on the design model which will produce and generate stress distribution [33, 34]. In bone implantation, it is crucial to simulate whether the design model could remain in place following the implantation as biological forces will act in all directions [35]. The material properties should be set to the design models to provide data to the software, in resisting the applied forces or loading once the simulation is run [36]. The material properties inclusion will affect the simulated outputs on mechanical strength, Young's modulus, elongation and deformation [36].

FEM 's theory breaks the solid body into several thin, easily shaped cells that will model the body's structure as precisely as possible [37]. Such small cells are referred as elements and the junction points between elements are known as nodes. The method of turning a robust body model into a FE model is called meshing that allows much simpler bonded solutions to replace a complicated engineering problem [37]. In order to find the most suitable number of meshes for the conduction of simulation and computational analyses, a convergence study of meshes is required [38]. Based on Kuang and Chang [39], the default median mesh should be used in the simulation mechanical analysis using Solidworks® to increase the homogeneity of stress distribution and to prevent wrong data interpretation. Some models are modelled with triangular elements and another form of tetrahedral elements could also be used to construct 3D scaffold geometries [5]. The unit size of element is very important to control the sensitivity of applied pressure [3, 5]. The smaller the unit size will produce more precise structure of 3D model and better stress homogeneity [5]. However, lowering the unit size will impact in greater element and nodes that will consume longer time for the accomplishment of simulation analysis depending on the workstation capability [3].

Boundary condition is required in the setting of FEM to provide constraint surfaces for the simulation analysis. In the study by Saidin *et al.* [36], three boundary conditions were set to the assembled of dental implant, teeth and two types of bone. On the other study by Jayendiran *et al*. [33], the boundary condition was applied at the interface between the outer surface of the blood and the stent inner surface for the transfer of continuous normal stress and continuous displacement. Figure 2 displays the placement of applied loading or loading force on the surface of 3D model bone scaffold and the setting of boundary condition on the opposite surface of bone scaffold. For the simulation in physiological environment, the surface or points of boundary condition must be properly selected based on the constraint surface or constraint point of the rigid organs and tissues.

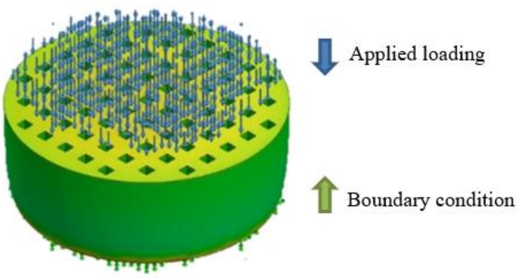

Figure 2. Placement of applied loading and boundary condition on 3D model bone scaffold using Solidworks®

6. Conclusion

The FEA methodology has provided reliable values which brings its application to the area of biomedical engineering. Simulation analysis is a new and cost-effective methodology to be applied in bone tissue engineering as an alternative to the conventional experimental methodologies. This review study is focused on the simulation analyses on bone scaffolds, specifically on the utilisation of Solidworks®.

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