MESH QUALITY IMPROVEMENT BY RE-TRIANGULATION SURFACE MESHES ON 3-DIMENSIONAL CAD MODEL OF A HUMAN WRIST JOINT

By

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Chairman: Tang Sai Hong, PhD
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With the recent advances computing technologies nowadays, reverse engineering is rapidly developing and has been strongly established many years in biomedical industry. Three dimensional geometric modeling is now being extensively used in many applications such as surgical planning, rapid prototyping, medical implants design, numerical simulation and etc. Thus, mesh quality is very crucial especially in finite element analysis in order to produce high accuracy results. Re-triangulation surface method is employed to improve the mesh quality of the model with certain parameters. The purpose of this study are a) to construct a complex three dimensional geometric CAD model of human wrist joint which contains cortical and cancellous bones using image-based processing method, b) to investigate the effects of triangle reduction, mesh smoothing and size of triangle mesh on the accuracy and mesh quality of the wrist bones model and c) to optimize the mesh quality using response surface methodology (RSM). A three dimensional CAD model of a human wrist joint was constructed after conversion model to non-uniform rational B-spline (NURBS). Re-triangulation process was carried out by manipulating different values of the parameters like geometrical error, smoothing factor and control edge length of triangle mesh along with mesh quality analysis in order to get high quality of mesh on the triangular surface wrist joint model. Lastly, optimization was performed via RSM to optimize the high quality mesh on the triangular surface model. In the findings, triangle reduction with geometrical error of 0.05 mm had reduced the number of triangles of cortical and cancellous bones to 74.81 % and 75.34 % respectively while obtained 70.05 % and 68.69 % of high quality of mesh on the surface model respectively. In term of accuracy, no significant changed in surface area and volume. For mesh smoothing effect, smoothing factor of 0.8 was selected to obtain 87.53 % and 86.68 % of high quality of mesh on cortical and cancellous bones respectively. For control size of triangle mesh, 0.5 mm of control edge length of triangle was taken to produce 92.35 % and 92.09 % for cortical and cancellous bones respectively. In term of accuracy of the model, the surface area and volume of the cortical and cancellous bones had no significant changed with less than 0.15 % and 0.25 % compared to the initial bones model. In RSM optimization, the optimum mesh quality on cortical and cancellous bones were 90.74 % and 89.67 % respectively. In conclusions, the mesh quality and accuracy of the model show promising results with the process of re-triangulation surface and the high quality mesh of optimum models were obtained using RSM.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENINGKATAN KUALITI JARINGAN DENGAN TRIANGULASI SEMULA JARINGAN SEGI TIGA PADA 3-DIMENSI CAD MODEL TULANG PERGELANGAN TANGAN MANUSIA

Oleh

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Dengan kemajuan teknologi pengkomputeran pada masa kini, kejuruteraan balikan berkembang dengan pesat dan stabil dalam industri bioperubatan. Model 3 dimensi (3D)- geometri digunakan secara meluaskan dalam aplikasi seperti perancangan operasi, prototaip pantas, reka bentuk implant perubatan, simulasi berangka dan lain-lainnya. Dengan itu, kualiti jaringan memainkan peranan penting terutamanya dalam analisis unsur terhingga untuk menghasilkan keputusan yang mempunyai ketepatan yang tinggi. Kaedah triangulasi semula segi tiga pada permukaan dapat meningkatkan kualiti jaringan model dengan parameter tertentu. Tujuan kajian ini adalah a) untuk membina model 3 dimensi CAD kompleks pergelangan tangan manusia yang mengandungi tulang kortikal dan kanselus dengan menggunakan kaedah pemprosesan berasaskan imej, b) untuk menyiasat kesan pengurangan segitiga, melicinkan jaringan dan saiz jaringan segi tiga pada ketepatan dan kualiti jaringan darimodel tulang pergelangan tangan dan c) untuk mengoptimumkan kualiti jaringan dengan menggunakan kaedah gerak balas permukaan (RSM). CAD Model geometri tiga dimensi pergelangan tangan manusia dibina selepas diikuti dengan penukaran model kepada B-spline rasional yang tidak seragam (NURBS). Proses triangulasi semula dilakukan dengan memanipulasi nilai-nilai parameter yang berbeza termasuk ralat geometri, faktor pelicinan dan panjang pinggir segi tiga kawalan serta analisis kualiti jaringan untuk mendapatkan kualiti jaringan yang tinggi (ukuran bentuk segi tiga ≥ 0.8 merupakan ukuran kualiti jaringan yang tinggi) pada model sendi pergelangan. Akhir sekali, pengoptimuman dilakukan melalui RSM untuk mengoptimumkan kualiti jaringan segi tiga di permukaan model. Dalam kajian ini, pengurangan bilangan segi tiga, ralat geometri sebanyak 0.05 mm telah mengurangkan bilangan segitiga bagi tulang kortikal dan kanselus sebanyak 74.81 % dan 75.34 % masing-masing manakala 70.05 % dan 68.69 % menunjukkan kualiti jaringan pada model permukaan masing-masing. Dari segi ketepatan, tiada perubahan yang ketara di kawasan permukaan dan isi padunya.

Untuk kesan melicinkan jaringan, faktor pelicinan 0.8 dipilih untuk mendapatkan kualiti jaringan yang tinggi sebanyak 87.53 % dan 86.68 % bagi tulang kortikal dan kanselus. Bagi kawalan saiz segi tiga, panjang pinggiran kawalan 0.5 mm telah diambil untuk menghasilkan 92.35 % dan 92.09 % mewakili peratusan kualiti jaringan yang tinggi bagi tulang kortikal dan tulang kanselus. Dari segi ketepatan model, kawasan permukaan dan isi padu tulang kortikal dan kanselus menpunyai perubahan kurang daripada 0.15 % dan 0.25 % berbanding dengan model awal. Dalam pengoptimuman RSM, kualiti jaringan optimum bagi tulang kortikal dan kanselus adalah sebanyak 90.74 % dan 89.67 %. Kesimpulannya, kualiti jaringan dan ketepatan model menunjukkan hasil yang menjanjikan dengan proses triangulasi semula dan optimal model yang berkualiti tinggi didapati.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATONS

mm	Millimetres
λ	Wavelength
%	Percentage
R_1	Radius of inscribed circle
R_2	Radius of ascribed circle
2D	Two dimensional
3D	Three dimensional
GE	Geometrical error
SF	Smoothing factor
CL	Control edge length
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CAE	Computer-Aided Engineering
CARE	Computer-Aided Reverse Engineering
MRE	Medical reverse engineering
FEA	Finite Element Analysis
CFD	Computational Fluid Dynamics
NURBS	Non-uniform Rational B-spline
STL	Stereolithography
VRML	Virtual Reality Modeling Language
DXF	Drawing Exchange Format

RSM	Response Surface Methodology
CT	Computerized Tomography
RE	Reverse engineering
RP	Rapid prototyping
IGES	Initial Graphics Exchange Specification
VDA	Verband der Automobilindustrie
STEP	Standard for the Exchange of Product Data
DICOM	Digital Imaging and Communications in Medicine
ROI	Range of interest
NC	Numerical control
RSM	Response Surface Methodology
ANOVA	Analysis of Variance
CCD	Central Composite Design
k	Number of control variables
F	Ratio between the mean square
p	Probability of error value
R^2	Coefficient of determination
S/N	Signal to noise ratio

CHAPTER 1

INTRODUCTION

1.1 Human Wrist Joint

The human wrist joint is an essential joint of the upper extremity and plays a significant role in maintaining a normal daily life. It links the forearm to the hand. Unlike others bones joint like hip, elbow, shoulder, ankle and knee, wrist joint is one of the most complex joint in the anatomy of human. A healthy wrist joint should able to perform a normal functional range of motion. These movements of the wrist joint are separated into three categories which flexion-extension, radial-ulna deviation and forearm pronation-supination. Figure 1.1 illustrates these three degrees of freedom.

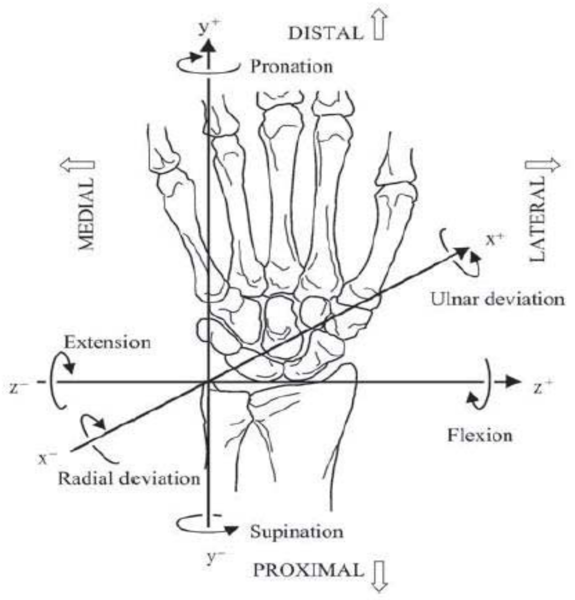

Figure 1.1 : Palmar view of the right wrist showing anatomical directions and rotations (SirkettMullineux *et al.*, 2004)

1.1.1 Anatomy of Wrist Joint

Wrist joint comprises of multiple articulations of the eight carpal bones with the distal radius and ulna. The carpal bones are separated into two rows, which are the proximal and distal. The proximal row is formed by scaphoid, lunate, pisiform and triquetrum while the distal row consists of trapezoid, trapezium, hamate and capitate (Bajuri & Kadir, 2012; Gislason et al., 2009).

The wrist consists of three main joints which are midcarpal joint, radiocarpal joint and distal radioulnar joint. The most movement and critical articulation in the joint is the radiocarpal joint, which is a synovial articulation formed by the distal end of the radius and the scaphoid, lunate and triquetrum (Bajuri & Kadir, 2012; Shepherd & Johnstone, 2002, 2005).

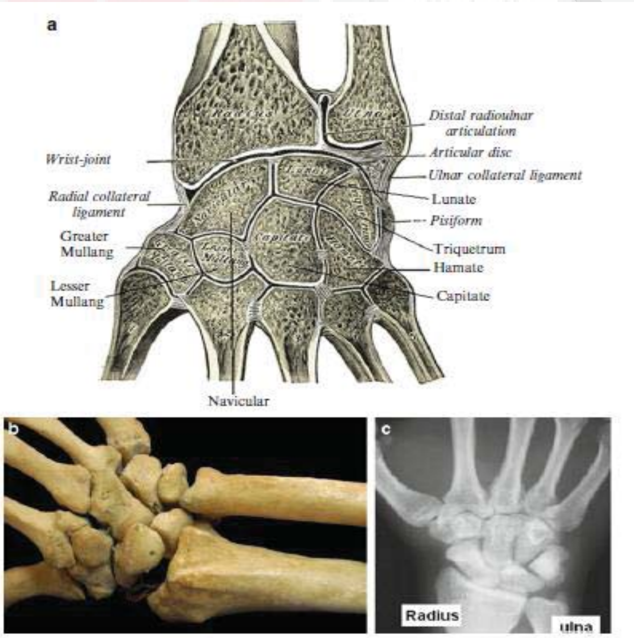

Figure 1.2 : (a) Wrist joint features; (b) the bones; and (c) the X-ray view (Pal, 2014)

1.1.2 Common Wrist Problems

The most common causes of wrist pain are due to highly frequency, duration and intensity activities. For examples, certain leisure, and working activities such as typing, sewing, cooking, and etc. in longer period and same routine of movements may be the factors that cause in wrist pain. Wrist injuries that caused by sudden impacts may leads to bone fracture. Besides that, wrist injuries are very common in many sports; either involves repetitive stress or impacts. These sports can be consisting of boxing, rugby, badminton, tennis, golf, bowling and etc. (Pereira, 2015). Also, some wrist fractures are caused by osteoporosis. In other hand, sprains and strains, tendinitis, arthritis and gout are the common causes of wrist pain.

Meanwhile, Rheumatoid Arthritis is the most common skeletal disease occurred in the wrist joint (Bajuri *et al.*, 2011; Stegeman *et al.*, 2005). Patients with this wrist disease suffered severe pain, deformity and unable to perform normal range of motion. Due to the weakened and damaged ligaments, articular cartilages, tendons, joint capsule and together with eroded bones which unable to full support within the bones, eventually the wrist joint becomes unstable (Bajuri, et al., 2011; Shepherd & Johnstone, 2002; Stegeman, et al., 2005).

1.2 Computer-aided Reverse Engineering

The process of engineering mainly focuses in designing, manufacturing, assembling and maintaining systems and products. Engineering can be divided into two types: forward engineering (FE) and reverse engineering (RE). The definition of the terms FE and RE are strongly dependent on the end-use applications and the field of study. Forward engineering usually can be defined as the conventional process of building an original part or total product with own ideas, innovative and logically. Meanwhile, reverse engineering is another way round. It can be defined as a process of duplicating and existing part, subassembly or product, without any technical details such as drawings, bill-of-material, or without engineering data (Chikofsky & Cross, 1990; Hieu, et al., 2010; Raja & Fernandes, 2007; Wang, 2011).

Reverse engineering is a multidisciplinary applied science and almost can be applicable to every case of fields (Wang, 2011). It is now widely used in many areas such as industrial, design and manufacturing, automotive, artistic and architectural, software engineering and biomedical (Raja & Fernandes, 2007; Šagi *et al.*, 2015; Wang, 2011). In terms of cost and time consuming, this method is more preferable than the conventional engineering because it is less expensive and time saving in designing part especially in creating a complex geometrical model (Raja & Fernandes, 2007; Šagi, et al., 2015). According to authors, the definition of computer-aided reverse engineering is a technique to create a geometric 3-D model by digitizing the scanned data to form multiple 3-D points or re-triangulate mesh from the scanned object (Raja & Fernandes, 2007). This process can be described as follow in Figure 1.3.

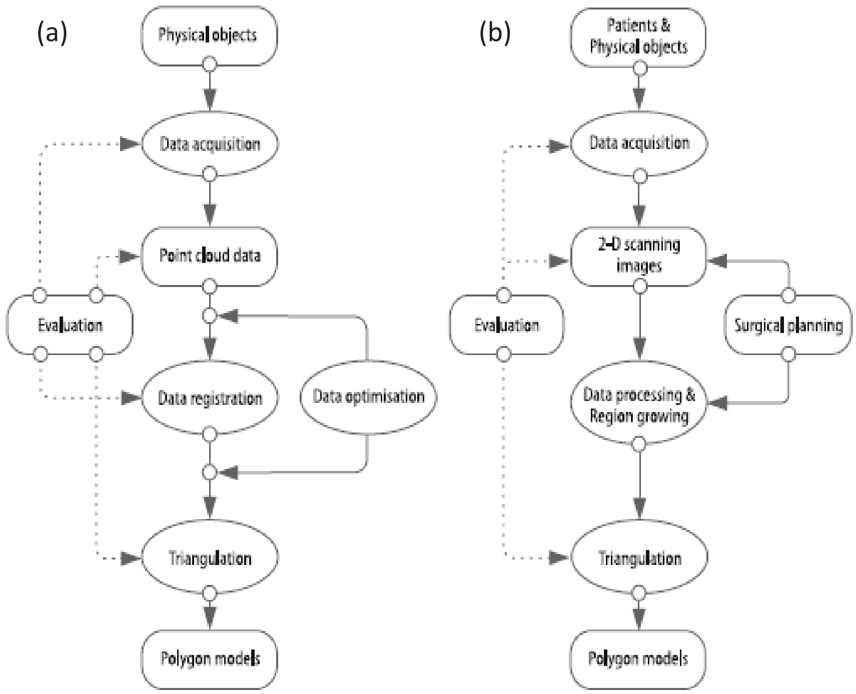

Figure 1.3 : A flowchart for modeling 3D triangular mesh models with different scan data input. (a) Point cloud data as the input. (b) 2-D scan images as the input (Raja & Fernandes, 2007)

1.3 Three Dimensional Geometric Modeling

A three dimensional (3D) geometric model is a digital representation consists of geometry data information formed in virtual environment which can be then used by computer-aided design, manufacturing and engineering (CAD/CAM/CAE) applications (Relvas *et al.*, 2011; Šagi, et al., 2015). 3D geometric modeling has been widely used in biomedical with the aid of reverse engineering. Generally, patient data or biomedical objects are required in the modeling of 3D geometric models. The reconstruction of 3D models normally involved anatomical structure, tissues organs, medical implants, surgical planning and biomedical research (Hieu *et al.*, 2010; Šagi, et al., 2015).

Before 3D geometric modeling of the object is ready for visualization, data exchange or manufacturing applications, the geometrical model has to be discretized into a 3D polygons mesh or NURBS mesh either from the input of point clouds or 2D image planes. For data exchange, different output files are converted for different applications purposes. (Bénière *et al.*, 2013; Hieu*, et al.*, 2010).

1.4 Type of Elements

There are many type elements available such as triangle and quadrilateral as surface mesh in 2D while tetrahedron, hexahedron, pyramid, prism with triangular base and arbitrary polyhedron as solid mesh in 3D. Figure 1.4 shows different type of elements available.

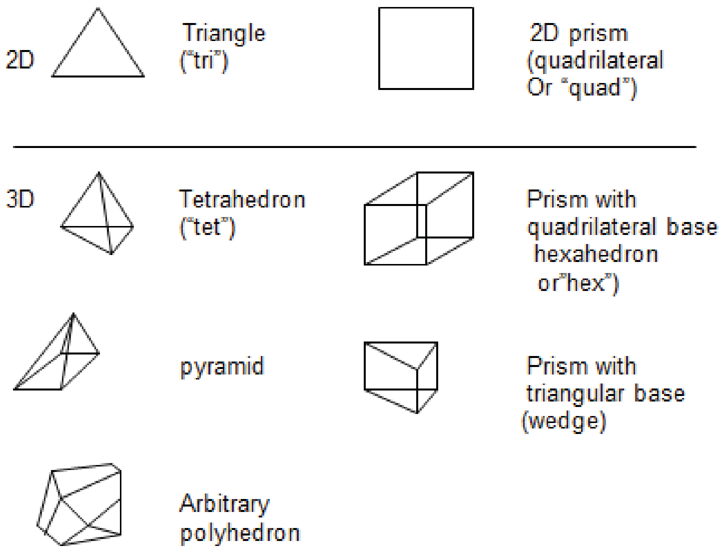

Figure 1.4 : Type of different elements available (Bakker, 2013)

Triangle is the simplest polygon that formed with three vertices and three edges connected to each other. Triangular surface mesh is more prefer in geometric modeling because of its properties to represent geometries of objects (Hieu, *et al.*, 2010). Besides that, it can easily converts to tetrahedral mesh. Due to its simple, flexible and quite strong adaptability to complicated boundaries properties, tetrahedral mesh are widely used to modeling complex geometries objects for numerical simulations (Sun *et al.*, 2010).

1.5 Problem Statements

The human wrist joint is one of the most complex joint bones that play a significant role in maintaining normal daily life activities. Although there have been extensive research into the anatomy of the wrist and its separates components, the biomechanics of the wrist still has a long way to study and understood deeply. Developing a 3 dimensional wrist joint remains high challenges due to the complex geometry, large amount of articulations, non-linear properties of supporting soft tissue structures and the inter-relationship between all of these components. Therefore, there was noticeably lack of literature concerning wrist joint finite element modeling compared to other simple joint bones. Additionally, software and hardware computational speed was one of the factors leads to less research studies on this field for past decades (Gíslason *et al.*, 2010).

With the advanced technology recently, reverse engineering was introduced to the biomechanical industry, creating a full, geometrically accurate and models are more feasible using medical image processing method. However, (Hieu, *et al.*, 2010) claimed that it was hard to adequately meet the requirements in data processing and geometrical modeling works with a single software. Consequently, it depends on the end-use application on the selection of the software because the processes of geometrical modeling and data exchange among the packages are very complex (Hieu, *et al.*, 2010).

The authors claimed that converting triangular surface mesh to tetrahedral (solid mesh) outside finite element solver was way easily and better control of the density and quality of the surface mesh. Besides, less works to be done after imported the model into finite element solver. Hence, this made the process more time saving without losing the geometrical integrity (Gíslason, *et al.*, 2010).

A tetrahedral mesh is basically formed by using a triangular mesh boundary and fill in with volume. If a self-intersection occurred in the boundary of triangular mesh, the mesh could not performed a well-defined volumetric mesh, and the tetrahedral mesh generator may create severely distorted elements or even fail to create a mesh at all. Therefore, it is necessarily to remove a self-intersection in a triangular mesh (Yamakawa & Shimada, 2009).

Moreover, most of scanned geometry model generated by using image-based method were saved in stereolithography (STL) file format often contained irregular, highly skewed and too dense of triangles. Such triangulation effectively prevents the creation of a good volume mesh. Improper surface mesh could not be used in numerical analysis such as finite element analysis (FEA) and computational fluid dynamics analysis (CFD) because of the mesh quality of the triangles were not sufficient to run an accurate simulation analysis (Magne, 2007).

1.6 Objectives

The aim of the study is to develop a complex 3D geometric CAD model of human wrist joint with high quality triangular surface meshes for future numerical simulation research purpose.

The objectives of this study are as follows:

1. To construct 3D human wrist joint CAD model which contained cortical and cancellous bones using image-based processing method.

2. To investigate the effects of triangle reduction, mesh smoothing and control size of triangle mesh with respect to the accuracy and mesh quality of the wrist joint model.

3. To optimize high quality triangular mesh using response surface methodology (RSM).

1.7 Scope of Study

First, all of the experiments in this research were performed using computational commercials software only. The commercials software that are 3D Doctor (Able Software Corp), Geomagic studio (Raindrop Inc.), Materialise 3-matic (Materialise, NV Belgium) and Design Expert 6.0 (Stat-Ease). No experiment in vivo was tested in the research. Only CT-scan data of a human wrist joint was used as resource in developing a 3D geometric wrist joint model. The CT-scan data was provided from Hospital Serdang, Selangor. The human wrist joint was assumed to be natural and healthy. The reconstruction of the geometric wrist joint model was only involved bones. Other tissues like cartilages and ligaments were neglected. The geometric wrist joint model was a triangular surface mesh model which means it was a shell model. Algorithms development and generation of volumetric mesh were not involved in this research. Mainly, this research was focused on calculations of mesh quality based on radius ratios of the triangle quality metric which found in computer software (Materialise 3-Matic). The re-triangulation parameters that are used in the study are geometrical error, smoothing factor and control length of a triangle which also provided in the computer software (Materialise 3-Matic). In order to preserve for good quality mesh, the parameters setting for re-triangulation process was set at 0.4 in the Materialise 3-Matic software so that mesh quality below 0.4 will not create on the 3D CAD model. Mesh quality of a triangle below radius ratios of 0.4 (<0.4) is considered low quality mesh while mesh quality of a triangle equal or above 0.7 to 1.0 ($0.7 \leq$ mesh quality ≤ 1.0) is considered as high quality mesh. Mesh convergence study was out of the scope of this study. For future research, this model can be used for finite element analysis simulation by converting it into volumetric mesh model.

1.8 Overview of the Study

In chapter one, a brief introduction is described about the human wrist joint, computer-aided reverse engineering, three dimensional geometric modeling, definition of triangulation mesh and mesh quality. In chapter two, previous studies related to the geometrical modeling using reverse engineering method and its biological applications are reviewed. Besides that, this chapter is also reviewed some previous works related on modeling of human wrist joint and other joint like knee, hip, ankle, shoulder, etc. On the other hand, mesh quality assessment of a triangular mesh, re-triangulation method and optimization study via response surface methodology are discussed in details.

Next, in chapter three it begins with a brief introduction about the research methodology and then by describing the work flow of reconstruction of human wrist joint model. In the subsequent experiments, three dimensional CAD modeling using NURBS fitting method after the surface model is repaired, smoothed and refined. After that, Re-triangulation process is taken place with the effects of triangle reduction, mesh smoothing and control size of triangle mesh. Optimization via response surface methodology is employed in the final of this chapter.

In chapter 4, results throughout the study are discussed in particular. It begins with the reconstruction of 3D human wrist bones model. Then it follows by the discussion about the influences of triangle reduction, mesh smoothing and control size of triangle mesh in aspects of mesh quality and validation of the model based on surface area and volumes after re-triangulation process process. Lastly, findings in the development of regression model, parameter study and optimization of mesh quality via response surface methodology for each cortical and cancellous bones are discussed in details.

In the final chapter, conclusion of the study is made and possible recommendation for future research is listed.

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