Comparative Biomechanical Analysis of Lumbar Disc Arthroplasty using Finite Element Modeling

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Abstract— **Lumbar total disc replacement (LTDR) is a surgical procedure for the treatment of degenerative disc disease (DDD) and lumbar spinal distortion to preserve range of motion (ROM). The SB Charité™ is the first device for LTDR but it produces more complications and long-term issues, causing a shortage of SB Charité™ disc. Currently, the evolution of lumbar disc arthroplasty based on some criteria like prosthetics structure, biomechanical model, tissue engineering and biomaterials approach. The optimal biomechanical model is based on kinematic and kinetic parameters together to ensure a long-term implantation with a lower rate of damage from disc implant in the spinal column. The finite element method (FEE) of human lumbar spinal is advanced to support biomechanical modeling techniques which are related to biomaterials guideline for choosing better material for implantation. Therefore, this paper presented a 3D biomechanical FEM model of L1 to L3 lumbar spines by different types of discs and materials. We applied a compressive force, and compressive force plus extension moment to this model to calculate Tresca stress of annulus fibers, strain and von Mises stress on the vertebral endplate at each intervertebral level under COMSOL Multiphysics® software.**

Keywords— biomechanical model; COMSOL; finite element method.

I. INTRODUCTION

The lumbar degenerative disc disease (DDD) is considered one of the most musculoskeletal disorders that involved in low back pain (LBP). The lumbar DDD has greatly affected the structure of intervertebral disc (ID) and mechanics of the lumbar spine thus it led to a poor range of motion (ROM), muscle failure and continual disability [1]. According to the physiological function of ID, it is formed of three parts such as annulus fibrosis, nucleus pulposus and cartilaginous endplates which is allowed the daily complex motions with an elasticity between vertebrae [2]. The most popular surgical treatments for DDD are lumbar fusion (LF) [3] and the lumbar total disc replacement (LTDR) that used to reduce a discogenic pain and improve motion-preserving strategy [4]. However, longer follow-up of clinical studies discovered that the clinical suitability of LF and LTDR in vertebral column surgeries still are ambiguous because they didn't provide the total preventive impact to address the degenerative changes of lumbar segment [5]. Hence, numerous prosthetic disc designs are implemented to create an effective replacement of the ID for facilitating mobility of the lumbar disc, thereby reduction of the degenerative effects on the lumbar segments.

Lately, the design of LTDR devices went through many advancements including SB Charité™, ProDisc- L, Maverick disk, lumbar prosthetic elastic spine pad (LP-ESP), Active-L® and M6-L to handle some shortcomings in the long-term treatment like pain, migration, subsidence, fracture, mechanical stress and reactivity of metallic wear debris [1]. It found that SB Charite′™ III [6] is a stable device with 6 degrees of freedom (DOF) in translation and rotation that based on the concept of mobile bearing core, while ProDisc-L and Maverick have 3 DOF with a fixed nucleus that based on the concept of a fixed axis of rotation. Additionally, SB Charite′™ III is a practical therapy for LTDR with the short term in lower lumbar damages. The Active-L® disc [7] is a modern device for permitting ROM and supplying a good simulator for treatment of degenerated lumbar.

It is important to note that the combination of several fields like surgery, pathogenesis, biocompatibility, biomaterials and biomechanical behavior is required for guaranteeing the successful disc arthroplasty [8]. The biomechanical technology of disc replacement devices has steadily developed to establish the best mimics for a healthy ID and protect patients against the risk of spine surgery. Also, the biomechanical designs of spine [9] acted as a complementary to the operative approach of LTDR that depended on used biomaterials. Biomaterials of disc implantation are classified according to their bearing surfaces, friction couples, motion stability, and anchorage [10]. For biomechanical testing techniques, the modeling of lumbar spine is summarized in four loading status: flexion, extension, left /right lateral bending and left / right axial rotation [11]. Over the years, biomechanical studies of LTDR have approached by finite element method (FEM) in order to restore spinal motion and maintain the surrounding tissues like the facet joints or adjacent segments [12]. Borkowski et al [13] proposed a prosthetic disc modeling for estimating the characteristics of force /displacement and moment /angle under different situations like compression, sagittal bending, shear and axial rotation. Rohlmann et al [14] examined a FEM model of the L3-L4 lumbar segment under different motions and reported the increase in the facet joint force and von Mises stress in the annulus as well as a decrease in intradiscal pressure. Park et al. [15] applied the FEM approach on the L4-L5 lumbar segment motion that based on compressive forces and bending moments for studying the lumbar spine biomechanics. This model demonstrated that reduction in inter-segmental rotations for flexion/ extension movements, reduction in intradiscal pressure for all motions, increase in facet joint forces, and increase in von-Mises stress within annulus for all motions. Cunningham et al. [16] focused on the evaluation of biomechanical analysis for intact spine, SB Charite`™ disc, BAK cages and ISOLA pedicle screw by using 3D flexibility testing and cadaveric model. According to the developmental phases of ID arthroplasty, Kim et al. [17] utilized biomechanical performance for three implanted models in the lumbar spine using FEM and compared the results of flexion and extension loads. On the other hand, Erbulut et al. [18] developed a 3D FEM model of L1–L5 lumbar spine for biomechanical changes assessment of an interspinous process (ISP) device that based on hybrid protocol. This model displayed that intradiscal pressure and the facet loads are increased after ISP implantation. Recently, Fu et al. [19] investigated the biomechanical influence on ISP device in eight patterns of the lumbar segments that based on lumbar fixation surgery and found that the degeneration of the lumbar segment is decreased due to minimizing the strain level of the facet joint. The biomechanical effects of disc pressure and facet strain [20] are measured after treatment with the SB Charité™ III disc under preload conditions.

Therefore, the advanced industrial technology of materials served the progress of comparative biomechanical models before the implementation of LTDR devices. In this paper, the biomechanical analysis of lumbar segments is applied to different types of materials and discs using a FEM technique. This study is focused on material and geometrical modeling to guide surgeons in the selection of a relatively better lumbar arthroplasty devices.

II. MATERIAL AND METHODS

The proposed model evaluated the biomechanical performance of L1 to L3 lumbar segments that implanted with the Charité™, Activ-L, ProDisc-L and M6-L discs and compared with the intact spine, using different materials including cortical bone, cancellous bone, titanium, steel AISI 4340, cobalt-chromium (Co-Cr) and aluminum. In this study, the material properties of ID and mechanical loading underwent many changes to decide the best biomechanical model for lumbar segments with avoiding the degenerated discs. This model is performed for studying the stresses, strain, and displacement of biomechanical loads on lumbar vertebrae levels using COMSOL Multiphysics® program [21]. Therefore, this FEM model is divided into four phases which are implant material choice, geometric modeling for intact spine and four implanted discs, analysis of loading modes for each model, and biomechanical evaluation for kinematic and kinetic measurements of spinal motion.

A. Geometric Models

The cross-sectional shape of geometry analysis for intact spine model is illustrated in Fig.1 (a). The lumbar geometry of intact model is divided into finite elements to generate a mesh structure as in Fig.1 (b). The FEM structure of L1 to L3 lumbar segments consists of three vertebrae, two ID, three-facet joints, supraspinous/ interspinous ligaments and spinous process as shown in Fig.1 (b).

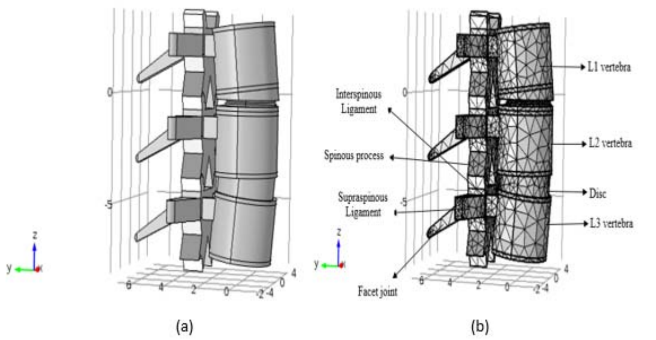

Fig. 1. *Intact spine model of the lumbar spine (L1 to L3) for (a) Geometrical analysis, (b) Mesh analysis by finite element model*

This mesh is used for creating a 3D model of the L1 to L3 lumbar segments. In this study, the geometrical analysis of implanted models with cortical bone and cancellous bone at different locations are designed in Fig.2 (e) and Fig.2 (f) respectively. Also, the geometrical analysis of implanted models with titanium, steel AISI 4340, Co-Cr and aluminum are designed in Fig.2.

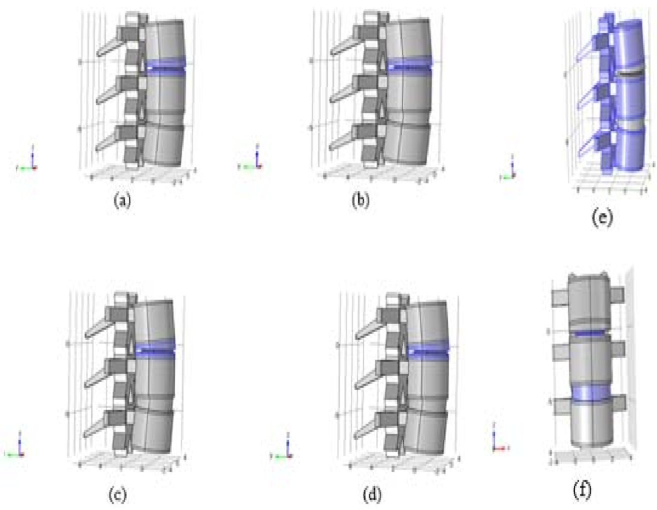

Fig.2. *Geometrical analysis of implanted models with (a) Titanium, (b) Steel AISI 4340, (c) Cobalt-chromium (Co-Cr), (d) Aluminum, (e) Cortical bone, and (f) Cancellous bone*

The SB Charité ™ is an unconstrained design and M6-L is elastomeric design, while Activ L and ProDisc-L are semi-constrained design [1]. The SB Charité ™, ProDisc-L, and Activ-L consist of metal-polymer-metal that based on mobile bearing and cobalt-chromium-molybdenum (CCM) / ultra-high molecular weight polyethylene (UHMWPE). On the other hand, The M6-L consists of 1-piece that based on titanium plates and polycarbonate urethane (PCU) / UHMWPE fiber core [22]. The polyethylene is a common material in medical implantation due to its wear resistance. Fig.3 represented the geometrical analysis of four implement discs.

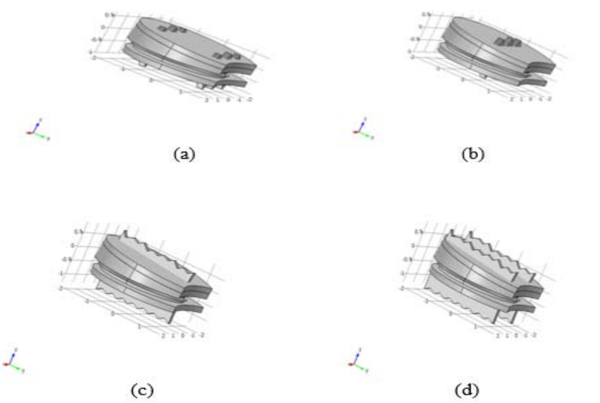

Fig.3. *Geometrical analysis of implement devices (a) Charité™ disc, (b) Activ-L disc, (c) ProDisc-L disc and (d) M6-L disc*

B. Material Choice

The mechanical properties of six materials regarding this model are listed in Table 1 with Young's modulus and Poisson's ratio. The choice of the biomaterial is significant to improve the surgical implant design and support the disc loading without vertebra curvature. The cortical and cancellous bones are considered as linear elastic materials [23]. The characteristics of titanium, steel AISI 4340, Co-Cr and aluminum [24] employed as bearing surfaces for providing the articular motions that may be useful for cervical TDR devices. According to the previous study, titanium was a good material for modeling of cervical prosthesis discs due to its high ability for corrosion resistant, its biocompatibility and its lower Young's modulus rather than other materials [25]. Generally, the quality of polyethylene wear debris is increased with titanium and deceased with Co-Cr. However, studies showed that titanium and Co-Cr have a poor wear resistance [26].

TABLE 1. MECHANICAL PROPERTIES OF THE MATERIAL FOR SPIN MODEL

Material	Young's Modulus (MPa)	Poisson's Ratio
Cortical bone	12000	0.35
Cancellous bone	100	0.25
Titanium	110000	0.28
Steel AISI 4340	205000	0.28
Cobalt-chromium(Co-Cr)	300000	0.27
Aluminum	70000	0.33

C. Loading Modes

The assembled parts of lumbar segments and discs with different materials are simulated under different loading modes namely, fixed constraint, boundary, and gravity. We applied loading modes on L1-L3 lumbar segments for calculating ROM during compression, flexion, extension, and lateral bending. The fixed constraint [27] consists of 3 DOF with a fixed nucleus to produce the good stability and anchorage. It allowed transferring the high forces within the vertebral plates to reduce the mechanical stress on lumbar segments. In boundary condition, the inferior endplate of the L3 vertebra is fixed and L1 to L3 lumbar segments have a free motion in three directions. It allowed distributing the similar loads to the endplate [28] which is called follower load [29]. The gravity load is focused on weight of the body segments and studied its effect on the mechanical manner of L1 to L3 lumbar segments. It is better to analyze the combination of follower load and gravity load to obtain the real representative of lumbar mechanics under a variety of activities. We applied the extension moment of 7.5 Nm on the x-axis of L1 and a follower load of 500 N for each level that already used in the literature [30].

D. Biomechanical Evaluation

All FEM models are simulated in a 3D structure including the anterior (X), left (Y) and upward (Z) directions. The total displacement, stress, and strain observed in four implant models. The maximum and minimum values of total displacement are applied to three lumbar segments. Also, the maximum and minimum values of von Mises stress and strain are applied on ID of L1 to L3 lumbar segments.

III. RESULTS AND DISCUSSION

This proposed model has conducted a 3D FEM model of lumbar segments L1 to L3 using COMSOL Multiphysics® program for an intact spine and models with lumbar prosthesis discs. The biomechanical evaluations which employed in this study are minimum /maximum of displacement, von Mises stress, Tresca stress, and strain for analysis of ROM in each 3D model. For materials choice, the experimental results showed that titanium is the best material for LTDR devices when compared with other materials. To analysis the motion of spinal segments, we compared a FEM model of intact spine with four implant devices by applying a compressive force in the follower load and compressive force plus extension moment. The different loading conditions are provided by the homogeneity of the applied forces. The compressive force in the minimum of total displacement, von Mises stress, Tresca stress, and strain are 500 N while the maximum of total displacement, von Mises stress, Tresca stress, and strain are 1250 N for each lumbar segment.

Under the loading conditions, total displacement and von Mises stress for Charité disc are designed in Fig.4. It was found that there are no significant differences between minimum and maximum for total displacement in Charité disc. On the other hand, the maximum von Mises stress for Charité disc is lower than maximum Tresca stress as shown in Fig.4 (d, f). The maximum Tresca stress had greater value on L1 and L2 vertebra which potentially discover the disc to damage. It also found that strain is increased in the disc between L1 and L2 segments.

For an Activ-L prosthesis disc, total displacement, and stress and strain are slightly similar in minimum and maximum values as shown in Fig.5. The results displayed that biomechanical stress is decreased at the facet joint and adjacent levels because the polyethylene core of the active-L facilitated the interpretation of the anteroposterior direction to allow for reproducing the normal physiological motion. However, the total displacement of Activ-L disc had greater load at facet joint of L3 vertebra than yield total displacement of Charité disc.

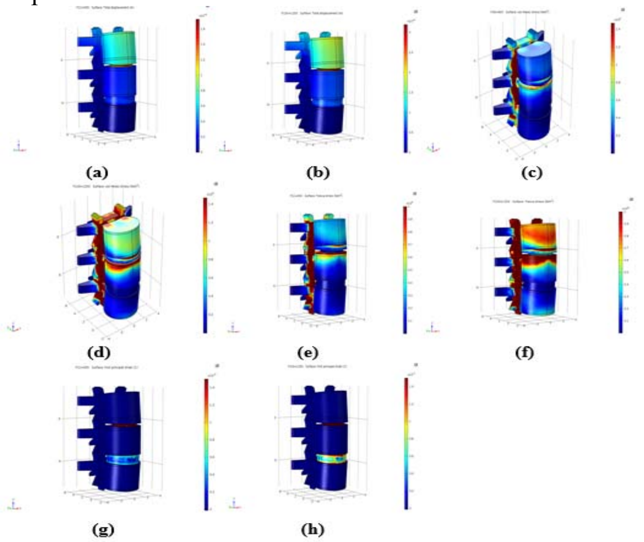

Fig. 4. *3D Model with Charité disc for (a) Minimum Total displacement, (b) Maximum Total displacement, (c) Minimum Von Mises Stress, (d) Maximum Von Mises Stress, (e) Minimum Tresca stress, (f) Maximum Tresca stress (g) Minimum Strain, and (h) Maximum Strain*

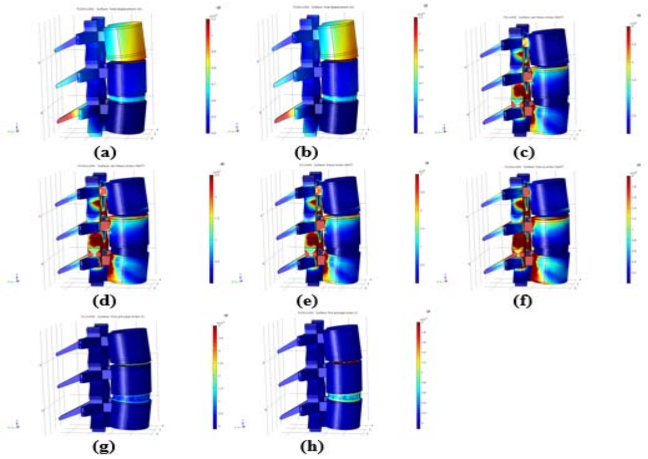

Fig.5. *3D Model with Activ-L disc for (a) Minimum Total displacement, (b) Maximum Total displacement, (c) Minimum Von Mises Stress, (d) Maximum Von Mises Stress, (e) Minimum Tresca stress, (f) Maximum Tresca stress (g) Minimum Strain, and (h) Maximum Strain*

In contrast, the ProDisc-L and M6-L discs are based on a limited center of rotation which is restrained ROM and led to injury during motions. The total displacement of ProDisc-L and M6-L discs had the greatest loads on L1 *vertebra* and facet joint of L3 vertebra rather than Charité and *Activ-L* discs as shown in Fig.6 and 7. In addition, the ProDisc-L and M6-L disc had von Mises stress and Tresca stress greater on third lumbar spine vertebra L3 and ligaments rather than at Charité and Activ-L discs as proved in Fig.6 and 7.

In this paper, the comparative biomechanical analysis of 3D spinal models for intact and four prosthesis discs that involved

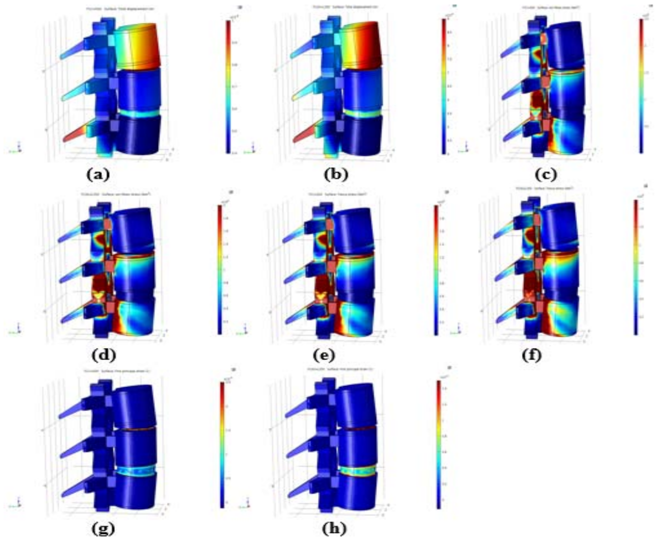

Fig. 6. *3D Model with ProDisc-L for (a) Minimum Total displacement, (b) Maximum Total displacement, (c) Minimum Von Mises Stress, (d) Maximum Von Mises Stress, (e) Minimum Tresca stress, (f) Maximum Tresca stress (g) Minimum Strain, and (h) Maximum Strain*

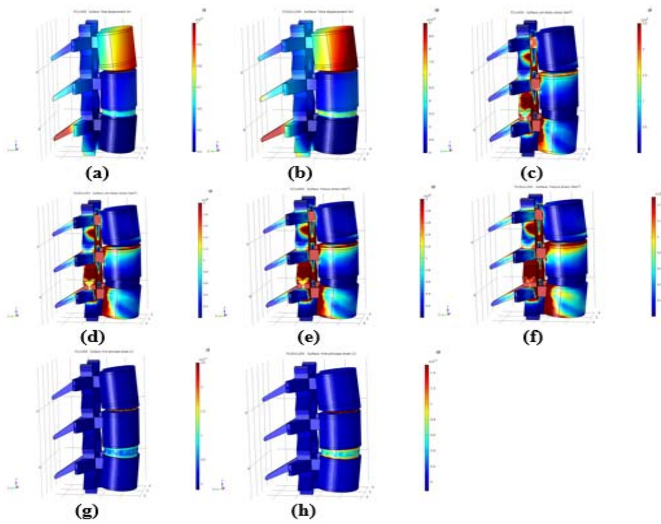

Fig.7. 3D Model with M6-L disc for (a) Minimum Total displacement, (b) Maximum Total displacement, (c) Minimum Von Mises Stress, and (d) Maximum Von Mises Stress, (e) Minimum Tresca stress, (f) Maximum Tresca stress (g) Minimum Strain, and (h) Maximum Strain

Charité™, Activ-L, ProDisc-L and M6-L discs under the same conditions are been reported by FEM approach and generated the mesh representation by COMSOL Multiphysics software. The main objective of these models is focused on predicting the accurate simulation of both the material and the geometry of ID which emanated from assistance clinicians to understand DDD effectively. Concerning the materials selection, the results are proved that titanium is favored for the modeling of L1-L3 lumbar segments. Therefore, the proposed biomechanical model is described in terms of total displacement, von Mises stress, Tresca stress, and strain under the fixed and boundary condition loadings for four prosthesis discs. The computations of COMSOL Multiphysics software confirmed that the differences in modeling of Activ-L, ProDisc-L and M6-L discs are relatively little when compared to Charité™ disc. The maximum stresses and strain of Activ-L, ProDisc-L, and M6-L discs are stronger than those of Charité™ disc thus three discs may lead to disc degeneration.

For comparative results, the previous works of lumbar modeling didn't available under COMSOL Multiphysics software. We observed the large increase in stress especially at the facet joint for all adjacent levels over prosthesis models. This is a noticeable stress increase in the previous study [18], which can be appeared for cervical spine models [31] because of restrictions of FEM analysis. Also, it was noted that strain for Charité™ disc is increased at the first ID and little decreased that equal to 0.6 at the second ID. It was found that the ROM had some restrictions that related to total displacement analysis for Activ-L, ProDisc-L and M6-L discs. Thus, the damage is increased to the first vertebra for ProDisc-L and M6-L discs rather than the other prosthesis discs.

On the other hands, the 3D of von Mises stress and strain for Charité™ disc are recorded the low loads rather than the other prosthesis discs as shown in Fig.4. The Charité™ disc model is qualified for predicting the response of the disc to the external loads.

IV. CONCLUSION

This model differentiated the biomechanical parameters in the lumbar spine of an intact and four implanted discs which showed the strength of lumbar spine is increased after SB Charité™ during extension moment. This study operated as a predictive model for treatment of the issues of disc reproduction.

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