A Prospective Finite Element Analysis of Proximal Interphalangeal Joint

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Abstract

Arthritis of the finger joints is a vital pathology of the hand. Among the surgical treatment of Arthritis is arthroplasty which involves replacing the diseased joint with an artificial joint. Surface Replacement arthroplasty SRA -PIP design consisting of two pieces, is used in this study due to its maintenance of locking ability along the length of the finger while retaining the shape, size and joint motion. The purpose of this paper is to develop a three-dimensional finite element model and study the muscular functions of different SRA-PIP design prostheses. Muscle forces such as grasp test, key test and pinch test are applied on PIP Implant Prosthesis. Based on the evaluation of FEA model, the best design is manufactured using Electron beam melting technology. Finally, an actual case study will be presented for demonstration purposes.

Keywords: Additive Manufacturing, Electron Beam Melting, Finite Element Analysis, Interphalangeal Finger Joint

1. Introduction

Common arthritis disease can affect any joint of the human-body and cause it to inflame, wear, and abrasion. It insures to affect the joint’s cartilage and cause it to degenerate over long periods; this disease causes the cartilage not to heal completely and leads it to wear until friction effects the joint to wear. Furthermore the arthritis disease affects mostly the elder range of people depending on their immune system which normally defends the diseases attacks. Sometimes it causes all the fingers to its symptoms or it causes just one finger. The difference between a normal joint and a diseased finger joint by arthritis are shown in Figure 1.
Arthritis occasionally is permanent on the joints where the immune system of the joint is failing. Nevertheless, it is like any other disease; its treatment is available nowadays and divided into two methods, surgical and non-surgical. Non-surgical treatment is always dealt physically and chemically; it includes medicines, injections, and natural trained exercise to rehabilitate the movement of the fingers. Surgical treatment is mostly effective and used when the joint is diseased enough to effect the natural ability of the hand functionality. The surgical treatment is defined in two types; arthrodesis and arthroplasty depending on severity. In arthrodesis, the bones of the joint are replaced with healthier bones and it is fixated by wires or biocompatible screws. Moreover, in arthroplasty, the bones of the joint are replaced by a biocompatible artificial prosthesis.

Nowadays, arthroplasty treatment efficiency is not defined by how well the surgery is done, but how well the artificial prosthesis is designed, what kind of biocompatible material used, and the fitting of prosthesis in the finger. Artificial prosthesis started by the silicon interpositional arthroplasty implants that was developed by Swanson, it was the most famous and preferred prosthesis in the treatment of the Proximal Interphalangeal Joint arthritis (PIPJ) [2]. Although, the silicone rubber prosthesis provided pain relief however its evaluation included several cases of implant fracture, implant looseness, and little range of motion [3].

This paper concerns about the design, manufacturing, mechanically testing, and biocompatible material of the four different designed prosthesis. Furthermore, as material efficiency is an important factor and due to the appalling evaluation of soft materials, hard material is preferred. In addition, titanium has many advantages in its properties especially Ti alloy-Ti6Al4V that is biocompatible, has the superiority in high fatigue strength, low elastic modulus, and corrosion resistance [4].

Nevertheless, the addition of a second material in the titanium prosthesis is important due to the friction of metal-on-metal prosthesis that has awful reputation [5]. The prosthesis should contain a highly durable material that has a very low friction with the titanium prosthesis. Therefore, the addition of the two vitamin-doped HXLPE material that contain a small amount of an antioxidant and alpha-tecopherol to prevent oxidation. This material would prevent or reduce the friction that is caused by metal-on-metal prosthesis [5].

Four different prosthesis are designed with the help of image scanning technology such as the Computer Tomography (CT). CT provides a three-dimensional shape of the joint which can be enhanced and designed with Three-Dimensional Computer Aided Design (3D-CAD) technology. The designed prosthesis can be further analyzed and tested with Finite Element Analysis (FEA) using (Ansys) to acquire the results from daily hand functions. Manufacturing the prosthesis is done by Electron Beam Melting machine. Concluding of reducing number of revisions, surgical time, and medical cost, decreasing prosthesis failure, and offer the best fit of dimensions.

2. Fabricating The Proximal Interphalangeal Joint Model Methodology
The stages of the development PIPJ prosthesis methodology as shown in Figure 2 involves of image scanning, designing & optimizing, mechanical testing & analyzing, fabricating & manufacturing. The following steps summarize the proposed methodology of designing the PIPJ prosthesis:
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- Image scanning of the patient’s hand using Computer Tomography & obtaining the Dicom format file.
- Using the medical imaging “MIMICS” software to segment the given files to conclude with the patient’s diseased finger then convert the file format into a IGES format file.
- Taking the IGES file & designing the prosthesis based on the patient’s PIPJ dimensions using the Computer Aided Design “CATIA” software and converting it into STL file.
- Manufacturing the prosthesis as a model polymer prototype using Fused Deposition Melting technology.
- Revising the polymer PIPJ prototype with an orthopedic surgeon to evaluate and change if needed the designed prosthesis.
- Mechanical & functional testing the designed prosthesis using the Finite Element Analysis “ANSYS” software.
- The prosthesis STL file is treated from errors and adding supports using “MAGICS” software then converting it into compatible Abf format for the EBD.
- Fabricating the final PIPJ prosthesis using EBD.

2.1 Scanning and Image Segmentation of PIPJ
The Computer Tomography (CT) consists of scanning X-rays that emits a series of beams that scans a specific part of the body. In addition, tomographic image slices are created; the scanned images are transferred to a computer as two-dimensional cross sectional images. Later then, the images are displayed on the computer screen to use it for diagnose and therapy purposes [6]. CT scan provides an excellent contrast between the differences of the soft tissues from the hard tissues of the body. Therefore, the CT scanner can provide an excellent visual diagnostic of the bones. Thus, scanning the patient’s hand, images of hand bones are produced. These images are stored as Digital Imaging and Communication in Medicine (DICOM) format. The medical software MIMICS (Materialise's Interactive Medical Image Control System, Belgium) is used to read these digital images and convert the two-dimensional images into a three-dimensional mask as shown in Figure 3. Also, digital images can be manipulated by using segmentation and region to obtain the required body part as shown in Figure 4 [7].
2.2 Design and Fit & Evaluation testing using FDM fabrication
The PIPJ finger prosthesis design can be formed in two types of designs. Mono-block type that is one part design such as the Neuflex prosthesis and the Modular type that is two-part design such as Chow prosthesis as shown in Figure 5.

Figure 5: Chow and Neuflex Prosthesis, respectively [8]
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In the design of the PIPJ prosthesis design criteria focuses on the biocompatible material, the shape, and the design type, the following summarizes the innovated designs:

**Basic Design (BD):** The “BD” prosthesis is the first constructed design based on the modularity of Chow’s prosthesis and built based on SR PIP prosthesis design. The basic design consists of Titanium Ti6A4lV material with two parts, proximal Component (a), middle Component (b), and the assembly of the prosthesis (c) are shown in Figure 6.

![Figure 6: Basic Design of the artificial implant](image)

**Improved Design (IMP):** The “IMP” prosthesis design was constructed based on the improvement and modification of the “BD” design. The improvements in “IMP” prosthesis consists of adding a new material polyethylene two vitamin-doped HXLPE with the Ti6A4lV. Furthermore, the two-parts of prosthesis; the proximal Component (a) was reshaped to increase flexibility, endurance, and stability on the bones. Moreover, the middle Component (b) consists of two different materials that are mentioned and also was reshaped to increase flexibility as shown in Figure 7. Polyethylene material is added to reduce the friction between the proximal & middle Component.

![Figure 7: Improved Design of the artificial implant](image)

**The Second Improved Design (IMP2):** The Basic Design second modification and reshaping is done to ensure the prosthesis have high flexibility, range of motion, and stability. Removing sharp edges from both components and reshaping the middle component (a) to result in a high range of motion, prosthesis assembly (b) as shown in Figure 8.

![Figure 8: The second Improved Design of the artificial implant](image)

**The Fins Design (FINS):** This final design accumulates all the improvements and modification that was done in the previous designs. The standard modification concerns about the stability of the prosthesis in the bones and its effects on the range of motion. However, in this design on the proximal Component (a) concluded with a very high stable stem with minimal looseness. In addition, to the improvements a locking mechanism is added to the middle
Component (b) to increase stability of the polyethylene to the titanium stem without the addition of any gluing material. The prosthesis assembly is shown in Figure 9.

![Figure 9: The Fins Design of the artificial implant](image)

The proximal joint includes the PIPJ and two phalanges connected to the joint, the middle phalange is connected to the middle component (a) and the proximal phalange (b) is connected to the proximal component. These phalanges are approximately shapely designed as shown in Figure 10 to connect them to the artificial prosthesis. These phalanges are designed to mechanically and functionally test the PIPJ using grasp, key pinch, and tip pinch tests. The assembled proximal joint are done through two different angles 85° and 135°; Thus explaining the 85° angle for the grasp & key pinch test, and the 135° for the tip pinch test.

![Figure 10: The Proximal Joint Phalanges](image)

**FDM Fabrication:** The designed PIPJ prosthesis is fabricated using Fused Deposition Modeling (FDM) technology as shown in Figure 11. Furthermore, a consultative orthopedic doctor ensures that the designed prosthesis fits the required joint criteria such as range of motion, stability, and looseness. The FDM technology provides a prototype that has a clearer view of the defects and allows the surgeon to plan for the procedure, experience for operations, and diagnostically feasible. [9, 10].

![Figure 11: Prototypes of artificial implants using FDM](image)
2.3 Finite Element Analysis Procedure
The Finite Element Analysis (FEA) is done through ANSYS software, the ANSYS can upload the CAD designed prosthesis model that is produced from CATIA software. Therefore, the designs are analyzed by three tests: (1) Tip Pinch, (2) Key Pinch, and (3) Grasp. Thus, certain forces values in Newton units are obtained through the averages that are previously tested on the human hand and PIPJ as shown in Table 1 and Table 2.

<table>
<thead>
<tr>
<th>Hand Function</th>
<th>Strength (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tip pinch</td>
<td>24-95</td>
</tr>
<tr>
<td>Key pinch</td>
<td>37-106</td>
</tr>
<tr>
<td>Grasp</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Distal Phalange</td>
</tr>
<tr>
<td></td>
<td>Middle Phalange</td>
</tr>
<tr>
<td></td>
<td>Proximal Phalange</td>
</tr>
</tbody>
</table>

Table 1: Average strength of the index finger

<table>
<thead>
<tr>
<th>Hand Function</th>
<th>PIP Joint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tip Pinch</td>
<td>4.4-4.9</td>
</tr>
<tr>
<td>Key Pinch</td>
<td>4.9-19.4</td>
</tr>
<tr>
<td>Grasp</td>
<td>4.5-5.3</td>
</tr>
</tbody>
</table>

The analytical decisions in ANSYS require the mechanical properties of the titanium, HXLPE, and bones as shown in Table 3. Furthermore, the analysis is done through stress-strain distribution and deformation experiments of the prosthesis implanted in the bones as shown in Figure 12.

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Ti-6Al-4V</th>
<th>VitaminE-doped HXLPE</th>
<th>Bones</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>4500 Kg/m^3</td>
<td>0.926 - 0.945 gm/cm^3</td>
<td>1900 kg/m^3</td>
</tr>
<tr>
<td>Young's modulus</td>
<td>120 Gpa</td>
<td>930-990 MPa</td>
<td>80 Gpa</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>900-1200 Mpa</td>
<td>22.4 - 23.2 MPa</td>
<td>60-70 Mpa</td>
</tr>
</tbody>
</table>

Table 3: Material Properties for the FE prosthesis analysis [12]

2.4 Manufacturing the PIPJ Using Electron Beam Melting Technology
Electron beam melting is a digital direct manufacturing machine and used in various medical applications [13, 14]. The EBM use an electron beam that melts the powder of a certain metal material to develop a layer thickness of 0.1 mm [15]. Furthermore, to fabricate the designed prosthesis requires importing the STL file into MAGICS software to treat by removing errors and adding support model. Also, MAGICS produces accurate specifications and exports
the file as an ABF format. Moreover, the ABF files are exported in a disc and then loaded into the EBM to produce titanium based prosthesis as shown in Figure 13.

![Figure 13: Produced titanium based prosthesis](image)

Afterwards, the processed titanium implants are loaded into the Arcam’s Powder Recovery System (PRS) for clearing any attached grains. Also, the finished prosthesis requires a type of surface finish method in order to soften the surface and that could be done by any ordinary manufacturing process. Finally the prosthesis is sterilized through a standard cleaning solution.

3. Results and Discussion

The Analytical results in both experiments stress-strain distribution and deformation are in Pascal & Meter units, respectively. Moreover, using the previously mentioned three tests: Grasp, Key Pinch, and Tip Pinch, are used on each of the four designs producing 24 results as a total as shown in Table 4 that summarizes all the tests values in both of the experiments in each prosthesis.

### Table 4: Experiments results

<table>
<thead>
<tr>
<th>Tests</th>
<th>BD</th>
<th>IMP</th>
<th>IMP2</th>
<th>FINS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Deformation (m)*</td>
<td>Equivalent Stress (Pa)*</td>
<td>Total Deformation (m)*</td>
<td>Equivalent Stress (Pa)*</td>
</tr>
<tr>
<td>Grasp</td>
<td>1.7466e-005</td>
<td>4.253e+007</td>
<td>6.291e-005</td>
<td>1.7366e+008</td>
</tr>
<tr>
<td>Key Pinch</td>
<td>5.9283e-005</td>
<td>1.911e+008</td>
<td>9.5382e-005</td>
<td>2.3366e+008</td>
</tr>
<tr>
<td>Tip Pinch</td>
<td>6.1359e-005</td>
<td>8.12e+0007</td>
<td>5.1624e-005</td>
<td>6.2136e+007</td>
</tr>
</tbody>
</table>

*Maximum results

The following Table 5 shows the minimum results of both experiments that are shown in the previous table. Furthermore, the minimum values means that the prosthesis has the minimum effects of stress and deformation. In conclusion, the minimum values of stress and deformation happened on FINS and BD & IMP2, respectively.

### Table 5: Best Design Results

<table>
<thead>
<tr>
<th>Tests</th>
<th>Stress (Pa)</th>
<th>Deformation (m)</th>
<th>Best Design Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grasp Test</td>
<td>4.25E+07</td>
<td>1.75E-05</td>
<td>BD &amp; IMP2</td>
</tr>
<tr>
<td>Key Pinch</td>
<td>1.22E+08</td>
<td>5.15E-05</td>
<td>FINS</td>
</tr>
<tr>
<td>Tip Pinch</td>
<td>2.55E+07</td>
<td>5.10E-05</td>
<td>IMP2</td>
</tr>
<tr>
<td>Minimal Result</td>
<td>2.55E+07</td>
<td>1.75E-05</td>
<td>FINS</td>
</tr>
</tbody>
</table>

*Equivalent Stress (Pa)*
The detail of deformation FEA experiment in the “FINS” prosthesis is shown in Figure 14. In addition, the figure shows the end of the proximal and middle phalanges had the minimum deformity, while the maximum deformity was on the middle component of the prosthesis.

Furthermore, the mechanic forces and supports of the grasp test on the “FINS” prosthesis are shown in Figure 15. Moreover, the end of the proximal and middle phalanges consists of fixated supports due to its attachments with other joints; metacarpal and distal joints, respectively. As shown, the forces of the grasp test faces towards both of the phalanges and the PIPJ, concluding mechanical force and movement in the PIPJ.

4. Conclusion and Future Work
The experiments and analysis in this paper ensures that the prosthesis is well stable and has the required range of motion. The experiments such as equivalent stress and deformation concludes to an explanation that defines whether the prosthesis can be implemented or not. In conclusion, the minimal equivalent stress and deformation in the grasp test resulted on “BD” & “IMP”. In addition, the key pinch test and the tip pinch test minimal equivalent stress shares the same “FINS” prosthesis and the deformation minimal results for the key pinch happened also on “FINS”. However, the deformation in the tip pinch resulted on “IMP2” prosthesis. The minimal results have shared two prosthesis the “IMP2” and “FINS”. However, if any future key events related to this matter, could be to invent something that shares both of these prosthesis features with an orthopedic consultant in order to innovate a high functional design. Moreover, the prosthesis could be also analyzed and experimented in a vivo or a vitro model to provide real statistics of the functionality of these designs. Finally, the orthopedic surgeon could provide a real authentic hand and inserts the prosthesis into the hand in order to test the prosthesis mechanically and daily functionality.

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