Optimization of the structure of bionic finger segment prosthesis using generative design [version 1; peer review: awaiting peer review]

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Abstract

Background: Bionic hand prosthesis helps restore the original hand function. A survey on prosthetic users concluded that 79% thought that their devices were "too heavy". Therefore, the weight of the prosthesis is a major cause of user discomfort and fatigue. This research was aimed at the reduction of hand mass bionic prosthesis by optimizing the structure of the fingers with generative design methods.

Methods: The materials used were Acrylonitrile butadiene styrene plastic and Nylon 6, and the manufacturing method used Additive Manufacturing. The prosthesis was designed with a lighter finger structure with a max displacement of 2 mm and a maximum safety factor of 4.

Results: Generative design produced more than 80 designs. The selection of the best design was based on the status of design solutions, research limitations, visual aesthetics, recommendation values, and validation of mechanical performances. The best is the SS-2. This design has an 80% lighter mass with the highest safety factor of 3.79, the lowest stress of 5.26 MPa, and the maximum displacement of 0.61 mm.

Conclusion: Based on the exploration scheme, the generative design could produce more than 80 design solutions. The selection of the best design was based on the status of design solutions, research limitations, visual aesthetics, recommendation values, and validation of mechanical performances in the design. Design validation was carried out by simulating finite element analysis with static stress study methods in selected design candidates with input study cases similar to generative design exploration schemes. Finally, SS-2 design was the best design produced by the generative design method with the highest factor of safety value of 3.79. Also gives an advantage to a stress value of at least 5.26 MPa in cases of segment loading, as well as the maximum displacement value of 0.61 mm.
Keywords
Generative design, bionic hand, design optimization, finger prosthesis

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Introduction
In Indonesia, work accident data has recorded more than 120,000 cases until October 2020. Based on this data, there were 4,275 cases of disability. Psychologically, disability due to work accidents can lead to sadness, not being able to accept the change in one’s circumstances, feelings of anger, bordering suicidal thoughts. To reduce this impact, many technologies have been created and developed such as hand bionic prostheses to replace almost half of the original hand functions with a wide variety of driving systems of the prosthetic hand. Belter et al. (2021) who studied mechanical design and performance specifications of anthropomorphic prosthetic hands, showed that human hands have an average weight of 400 g at the wrist limit, excluding the weight of the forearm. Additionally, the survey of prosthetic hand users in the same study has indicated that 79% of users considered the prosthesis they use to be too heavy. Therefore, the weight of the prosthesis is a major contributor to discomfort and fatigue due to its use. 

Many prosthetic research studies have been found that focus on the development of components of the driving system. Examples include Shin et al. (2012) combining three drive system mechanisms: distributed actuation, dual mode twisting actuation, and EM joint locking mechanism. Ventigmilia (2012) used a gearbox on a thumb drive system. With this gearbox, thumb twisting motion was well-articulated. Gràcia (2015) utilized of 3D printing and self-assembly of driving systems and electronic components. Wang et al. (2017) developed a flexure hinge based on a two-electrode myoelectric control system. Dannereder et al. (2018) in effort to strengthen grip, they add driving force to the wrist using a linear drive system on each of the fingers.

To create a lighter and stronger bionic finger structure, there needs to be a design optimization study that uses generative design methods. In previous research, generative methods were also used in the optimization of a component. This method was chosen as a form of design automation in design exploration and optimization. Generative design is an optimization technology as well as a fast and easy cloud-based design exploration. As a global leader in design and technology, Autodesk believes that this method can provide more than one design alternative based on the design goals that have been determined using loading parameters, safety factors, materials, and manufacturing methods. As a result, this method simultaneously produces multiple design solutions based on predetermined design goals and limitations. The resulting design tends to have a more natural shape because of its approach that mimics the evolution of nature in design.

Generative design method has been discovered in recent research to make innovative design development. Francalanza et al. (2018) produced the robot manipulator designs with the same structural integrity, but with significantly minimized weight. Buonamici et al. (2020) designed a robotic gripper arm from ASTM A36 steel with a mass of 33.6 kg and a maximum displacement of 2.19 mm using Milling 5 axis manufacturing, which is lower than designs produced by additive manufacturing methods. Nisar et al. (2021) produced a mechanical pedal design that reduces weight by more than 40% and has a safety factor of 1.5. Matsunaka (2021) used milling manufacturing 5 axes to produce an arrowhead.
with a weight reduction of more than 50% from 1,531 grams to 633 grams. Rajput et al. (2021) produced lightweight foot and calf prosthetics using a combination of generative design and topological optimization. However, these studies did not explain the process of choosing the design of the many designs produced by the generative design. In addition, Buonamici (2020) stated that the designs produced by generative designs are very diverse, as they have different mechanical performance characteristics from one design to another. The consideration in choosing the best design as the final product is very unclear. Therefore, this study aims to determine the design selection steps based on reasonable criteria. In this research, optimization studies were conducted on the structure of the proximal segment of the finger (Figure 1), with a case study showing the hand in the hook grip position while carrying a 10 kg load.

Methods
Broadly speaking, this research is software-based because all activities from design to simulation rely heavily on the use of relevant software. The Autodesk Inventor Professional software (version 2021) with an alternative open-source version for student (https://www.autodesk.com/education/edu-software/overview?sorting=featured&filters=individual) was used to design bionic hands as research objects as shown in Figure 1. The generative design stage using Autodesk Fusion 360 was also used for the design validation stage. The validation stage used simulated finite element analysis (FEA) up to static stress studies.

Generative design scheme
The loading scheme on the bionic hand was achieved by using the hook grip position for lifting heavy objects (10 kg). In this position, the load was assumed to be equally distributed among the four finger segments, i.e., the index finger, middle finger, ring finger, and little finger. Therefore, the load on one proximal finger segment can be calculated by equation 1.

$$F_{\text{segment}} = \frac{F_{\text{total}}}{\text{number of segments}}$$

From equation 1, static load found on one finger segment was 2.5 kg or equivalent to 24.5 Newton. Considering the flexibility factor, the load was adapted to four different loading angles, including angles 90°, 75°, 60°, and 45°. The load

Table 1. Parameters of generative design.

| Parameter        | Value         |
|------------------|---------------|
| Load             | 24.5 N        |
| Max. displacement| 2 mm          |
| Min. safety factor| 2            |
| Material         | ABS plastic   |
|                  | Nylon 6       |

Figure 2. Generative design exploration scheme.
was applied to surfaces that were in direct contact with the objects, namely on the segment and the connection of the proximal segment with the middle segment. The direction of gravity was in line with the load. The optimization objective was a mass reduction with max displacement at 2 mm and min safety factor 2, summarized in Table 1.

The complete generative design scheme can be seen in Figure 2, where the preserved region or the part retained in the design is marked in red (fix geometry). Design exploration was carried out with two different configurations, namely without the starting shape and with the starting shape. The difference in the outcomes of the two categories will be coded as O and SS, respectively. The starting shape was the initial design of the finger segment, which was marked by dimensioned parts of the image. The bionic hand referenced the anthropometry of people aged 18 – 22 years.

Results
The generative design produced more than 80 design solutions or so-called outcomes that were divided into two categories of design solution status: completed and converged. Completed status is a design that has been successful through the generative design process, however the resulting performance does not meet the criteria of design parameters or errors occurred when one or more geometries are indicated separately. While the status of converged design solutions is a design with mechanical performance that has met the minimum criteria of design parameters. The results of generative design exploration have been summarized in Tables 2 and 3 based on the materials and manufacturing methods. In design solutions with additive manufacturing, there were limits in the form of manufacturing orientation direction, minimum thickness, and overhang angle. However, unrestricted manufacturing does not limit design solutions as mentioned above, therefore the geometry of the resulting design solutions tends to vary.

The results of the exploration were mapped on a scatter plot graph generated by the software (Autodesk Fusion 360 - Generative Design) in Figure 3. The graph makes it easy for users to map the mechanical performance of each design, within the constraints of mechanical performance which contains a design with converged solution status. The design with a maximum displacement of 2 mm and a factor of safety of at least 2 to a maximum of 4 falls under the limitation of the research.

Design selection
Within the parameters of the research limitation, there are 55 designs that have converged status. However, there needs to be observation and consideration in terms of visual aesthetics in each design. The generative design also provides recommendation values based on mechanical performance in each design. The value feature of the recommendation aims to assist the designer in making decisions on the final design to proceed to the next stage. It is expected that the analysis process can select the designs that have the feasibility of mechanical performance factors and visual aesthetics. Consideration factors used include design neatness and feasibility for the manufacturing process. Figure 4 shows visually identifiable defect design criteria based on (a) poor surface quality, (b) irregularly formed design geometry, (c) unsymmetrical geometry, and (d) geometry that exceeds the starting shape limit.

Defect design in generative design outcomes can be formed due to the adjustment of the limitations of manufacturing methods used as parameters of generative design. When the main parameters of mechanical criteria are maintained constantly on each outcome, the software sometimes fails to produce geometric details in the design. After careful

Table 2. Number of solutions by material.

| Material      | Completed | Converged |
|---------------|-----------|-----------|
| ABS Plastic   | 8         | 33        |
| Nylon 6       | 9         | 33        |
| Total         | 17        | 66        |

Table 3. Number of solutions by manufacture.

| Manufacture | Completed | Converged |
|-------------|-----------|-----------|
| Unrestricted| 3         | 57        |
| Additive    | 14        | 9         |
| Total       | 17        | 66        |
**Figure 3.** Scatter plot graph.

**Figure 4.** Design with defect criteria. (a) poor surface quality, (b) irregularly formed design geometry, (c) unsymmetrical geometry, and (d) geometry that exceeds the starting shape limit.

**Figure 5.** Design with feasible criteria.

| No. | Mat.       | Manufacture | Mass (kg) | Min Sf | Max displace, (mm) | Recommend Value (%) |
|-----|------------|-------------|-----------|--------|-------------------|---------------------|
| O - 2 | ABS plastic | Unrestricted | 0.006 | 2 | 0.30 | 80.5 |
| O - 22 | Nylon 6 | Additive | 0.003 | 2 | 1.84 | 79.0 |
| O - 30 | Nylon 6 | Additive | 0.003 | 2 | 1.46 | 77.1 |
| O - 24 | Nylon 6 | Additive | 0.003 | 2 | 1.41 | 77.0 |
| O - 3 | ABS plastic | Unrestricted | 0.007 | 2 | 0.25 | 73.8 |
| O - 12 | ABS plastic | Additive | 0.006 | 2 | 0.31 | 67.2 |
| O - 15 | ABS plastic | Additive | 0.007 | 2 | 0.25 | 60.7 |
observation, several outcomes have a better level of feasibility in terms of visual aesthetics or a design with feasible criteria that can be identified based on good surface quality, irregular and symmetrical design geometry, and a geometry that does not exceed the limit of the initial shape. The design with feasible criteria can be seen in Figure 5. Data on the mechanical performance of feasible design and the recommendation values of each category can be seen in Tables 4 and 5.

Based on recommended value, four designs with the highest recommended values from each category were selected. The design candidate can be seen in Figure 6 with different color identities, (a) O - 2, (b) O - 22, (c) SS - 2, and (d) SS - 6. Furthermore, design validation by simulation of finite element analysis (FEA) in static stress study with input study is the same as the exploration scheme of generative design in Figure 6.

Discussion
The simulation data is illustrated with a graph in Figure 7 that shows a ratio of factors of safety based on (a) load case segment and (b) load case pin. The SS - 2 design was superior even though the mass was lower than the O - 2 design in the

**Table 5. Feasible design data with starting shape.**

| No. | Mat.         | Manufacture | Mass (kg) | Min Sf | Max displace, (mm) | Recommend Value (%) |
|-----|--------------|-------------|-----------|--------|--------------------|---------------------|
| SS - 2 | ABS plastic | Unrestricted | 0.002     | 2      | 0.66               | 91.4                |
| SS - 26 | ABS plastic | Additive   | 0.002     | 2.3    | 0.64               | 75.2                |
| SS - 14 | ABS plastic | Additive   | 0.002     | 2.4    | 0.63               | 74.2                |
| SS - 22 | ABS plastic | Additive   | 0.002     | 2.6    | 0.62               | 71.5                |
| SS - 15 | ABS plastic | Additive   | 0.005     | 2      | 0.38               | 71.4                |
| SS - 23 | ABS plastic | Additive   | 0.006     | 2      | 0.35               | 69.1                |
| SS - 54 | Nylon 6     | Additive   | 0.002     | 3.88   | 0.78               | 58.1                |
| SS - 52 | Nylon 6     | Additive   | 0.002     | 4.3    | 0.61               | 55.3                |

**Figure 6. Best design candidates.**

**Figure 7. The factor of safety comparison graph.**
load case category. In the pin load cases category, the O-22 design was superior to other designs. But the factor of safety on the load case pin for this design was below 2. This is due to the highest stress experienced by this design in the case of loading.

However, the O-22 design had a higher Von-Mises stress value when compared to the SS-2 design. The graph in Figure 8 shows the ratio of stress based on (a) load cases segment and (b) load cases pin. The graph shows, the SS-2 design was superior with the lowest stress value of 5.26 MPa. The SS-26 design with a higher factor of safety value in the pin load cases category, had a greater stress value compared to the SS-2 design. Safety factors that were below 2 before, are in the same area as the highest stress area.

That is related to the geometry formed so that the distribution of stress in each design has different characteristics. Based on these observations, the O-22 design had many critical points on its geometry, while the other three designs had the same critical area. However, the critical area is very small as can be seen in Figure 9 which shows the critical areas of design (a) O-2, (b) O-22, (c) SS-2, and (d) SS-26.

Critical areas of design can be minimized in the post-processing by editing and adding more geometric volumes to the design. It can also improve the mechanical performance of the design with further analysis and observation to validate. The O-22 design had the highest displacement value compared to other designs. While the O-2 design with the lowest displacement value was superior in the category of pin load cases (Figure 10). But all displacement that occurred in each design was still below 2 mm.

However, in the category of load cases segment, SS-2 and SS-26 design had a relatively low displacement value in comparison to the O-2 design which is a maximum of 0.61 mm. This gives priority back to the SS-2 design. Therefore, according to the selection criteria introduced, the SS-2 design has been proven to have a better mechanical performance compared to other design candidates. The software’s recommended values in Table 3 for SS design-2 have also become more acceptable as the best result of this validation procedure. It also reinforces the reason for making the SS-2 design the best design produced by the generative design method. In addition, with the use of the generative design method, this
The study has indicated the process of choosing the best design with the following criteria illustrated in Figure 11. The criterion specified in this study can therefore be useful in future research that applies generative design methods.

**Conclusion**

Previous reports had shown that the weight of the prosthesis is a major contributor to the discomfort and fatigue of the amputee. As such, this study aimed to reduce the mass of the bionic hand prosthesis by optimizing the structure of the fingers with generative design methods. Based on the results of this study several conclusions can be drawn. Firstly, based on the exploration scheme, the generative design can produce more than 80 design solutions. Secondly, the selection of the best design was carried out through a sequence of criteria, including the status of design solutions, research limitations, visual aesthetics, recommendation values, and validation of mechanical performances in the design. Design validation is done by simulating finite element analysis with static stress study methods in selected design candidates with input study cases similar to generative design exploration schemes. Finally, SS - 2 design is the best design produced by the generative design method with the highest factor of safety value of 3.79. This design also gives an advantage to a stress value of at least 5.26 MPa in cases of segment loading, as well as a maximum displacement value of 0.61 mm.

**Figure 10.** Displacement comparison graph.

**Figure 11.** Diagram of the design selection process. GD - Generative Design.

Study has indicated the process of choosing the best design with the following criteria illustrated in Figure 11. The criterion specified in this study can therefore be useful in future research that applies generative design methods.
Data availability
All data underlying the results are available as part of the article and no additional source data are required

Author contributions
Agus Triono: Conceptualization, Format Analysis, Methodology, Supervision, Writing - Original Draft Preparation
Mahros Darsin: Methodology, Supervision, Writing - Review & Editing
Arsi Fathurrahman: Conceptualization, Modeling, Analysis, Writing - Original Draft Preparation
Nasrul Ilminnafik: Validation, Writing - Original Draft Preparation
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