Design and Analysis of a New Humanoid Robot Torso

Noor Zaheera Ishak, Nurul Syuhadah Khusaini, Norheliena Aziz, Sahril Kushairi, Zulkifli Mohamed

Abstract: ***The development of humanoid robot shows great significant in domestic, services and medical application. Humanoid robot is developed to aid human daily task. However, the appearances of the humanoid robot affect the robot's functionality as well as the acceptance of its usage in public. Hence, this study focuses on developing a new torso structure design for a humanoid robot for better performance. The new humanoid robot torso design is based on the actual human-like proportion and human torso structure. A 3D model of the torso has been designed and simulated in SolidWorks software. Aluminium is used as the raw material for the humanoid robot torso. The humanoid robot parts are fabricated via Computer Numerical Control (CNC) Machining and Water Jet Cutting. The design was then analyzed using Finite Element Analysis (FEA). Simulation results show that the new humanoid robot torso structure design is more stable and stronger where the maximum displacement for initial torso design is 9.715e-002 mm while after improvement is 6.783e-003 mm. The proposed system with 1 DOFs shows high strength and easy-to-control features and it is also proven that the simplified design is the best option to increase strength and stability.***

Keywords : Humanoid Robot, Upper Torso Robot, Finite Element Analysis, Pugh Method.

I. INTRODUCTION

Humanoid robot is designed for assisting human and improving the quality of our life. Humanoid robot is developed with human-like body shapes to mimick human appearances. Most of humanoid robot research focuses on the appearance, shape and the ability to co-exist with human. Thus, a human-like appearances is important for the robot to adjust with the human environment [1][2].

The humanoid robot also can be used as a personal assistant for human, especially the elderly due to the difficulty of body movement experience by them [3-5]. For example, the humanoid robot has been used to assist the elderly in nursing homes [6] and it has proven that humanoid robots are able to assist caregivers while taking care of the elderly.

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Traditional humanoid robots like ASIMO [7][8], HRP[9], BHR[10], HUBO[11], NAO[10], and iCub[12] are generally built with a box-shaped torso with only two or three degrees of freedom (D.O.F). For example, the torsos of the existing humanoid robots like ASIMO which represent the advanced level has only one rotary joint in the transverse plane [13].

The torso design usually has been neglected or simplified due to the complex control of the multibody system and mechanical design difficulties [14]. However, in many aspects of human-like movement and operation, the torso of a humanoid robot is important. Due to that, few researches had put forth the idea of developing humanoid robot with torsos which was inspired from the human torso.

From the previous research, it can be concluded that different design has different capabilities. The selection of design usually depends on what the purpose of the system is and how much accuracy does the system need [15][16]. Also, the torso does not require many degrees of freedom due to no body movement as documented in [17][18].

Since this study focuses on building a cost-effective system; selecting the most suitable design and material need to be implemented. Hence this study focuses on developing a new low-cost torso structure design for a humanoid robot for better performance.

II. DEVELOPMENT OF THE UPPER BODY

A. Design Process

In this project, the initial humanoid robot torso design was printed out using 3D printer and it consists of small parts with specified dimension. All parts were assembled and attached together by using adhesive or glue and contributing to the lower strength design structure as in Fig.1. Polylactic Acid (PLA) material is used for the torso due to its aesthetic and lightweight properties. However, the adhesive joint is fragile, and the part can easily experience a fracture. The structure of the robotic arm required the torso to be sturdy in order to support the arm and allow smooth movement. Thus, this paper proposed a single piece torso structure that could avoid unstable assembly. Criteria selection for the new concept had been generated via Pugh Method (PM).

B. Conceptual Design

Pugh method (PM) is a quantitative technique used to rank the multi-dimensional options of an option set.

PM is not weighted to allow a quick selection process by comparing the design ideas against the design criteria in the early phase of the design process. Based on the criteria, the PM had been constructed and shown in Table I. The criteria required to develop the torso design are shown in the PM table below. By utilizing this method, the best and optimized design can be selected. The scoring scale is Bad (1) to Good (10) and referring to the highest score, conceptual design 3 are selected as the final design (Fig. 2).

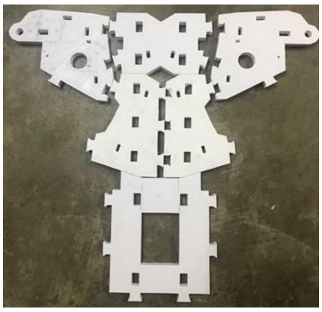
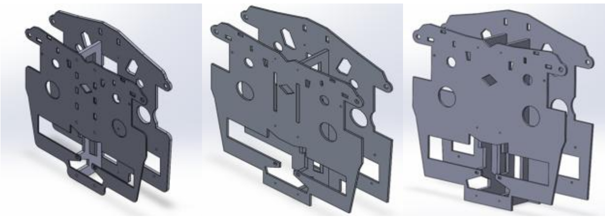


Fig 1: The initial design of the initial humanoid robot torso.



(a) (b) (c)

Fig 2: Conceptual Design (a) 1 (b) 2 and (c) 3.

Table I: Pugh Method for design selection

	Conceptual design		
Criteria	**1**	**2**	**3**
Easy to fabricate	5	6	8
Material strength	5(PLA)	9(Steel)	8(Aluminium)
Surface finish	8	6	8
Aesthetic value	6	5	8
Stability	5	8	8
Arduino component placement	5	6	8
Total	34	40	48

To begin the design process of the humanoid robot, few factors need to be considered. Firstly, the dimension of the torso must be based on the proportion of the human body. Secondly, the location of all servos at the torso for the arm motion need to properly aligned and considered. In order to identify the placement, various degree of freedom diagram of different robot available has been analysed.

C. Design Constraints

There is a lot of humanoid robot torso design developed in previous research. Most of the design has more than two degrees of freedom torso joint movement. For this project, the design has only single degree of freedom (1-DOF) that acts as the base to support and hold the head and upper limb of the humanoid robot. The aim of the design is to develop and build a robot torso based on human proportions that are capable of balancing and withstanding the load from the weight of the head, hands and all the components. The target mass for each part robot is 0.5 kg. Fig. 3 illustrates the Poppy robot; a robot that is inspired by actual human proportion [19].

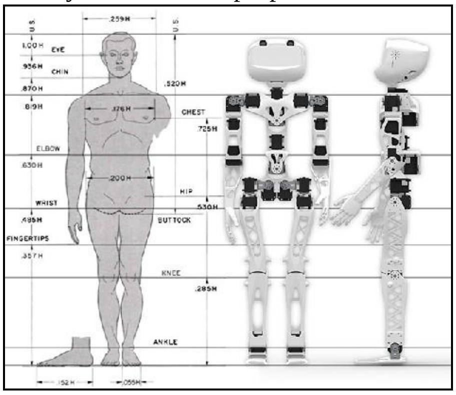


Fig 3: Human-like scale used for the design benchmark.

The design of a humanoid torso refers to the anatomy and capability of a human torso that is composed of a complex muscular-skeleton structure. The important role of a torso can be summarized as a central platform of a body; for organ storage and motion capability. The design must align with the shoulder joint and head, so that the motion of the limbs is smooth. Fig 4 shows the arm's section that will be assembled with the torso.

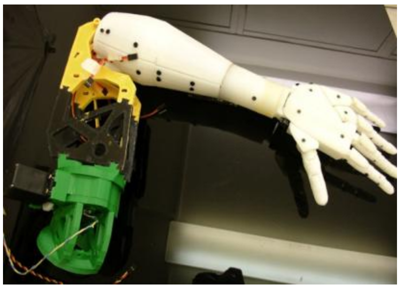


Fig 4: Arm section that will be attached to the torso.

Table II below shows the list of parts which are needed to be attached to the torso. All of the parts are fully-made from the PLA material.

Table II: List of part assembles with the humanoid robot torso.

Parts	*Weight (g)*
Hands	360
Forearms	440
Upper Arms	1080
Shoulder Joints	400
Head	1000

The total weight of the humanoid robot is inclusive of the actuator and Arduino components. The approximate total mass of the whole humanoid upper body is 4000 grams. The humanoid robot torso will be attached to the head and upper limb part in the next process.

D. Material Selection

In this research, the initial design of the torso utilizes PLA as raw material, but the strength is much lower if compared to aluminium. Aluminium is an alloy; where the alloying elements are silicon and magnesium. It is extensively used in architectural applications. It has very good strength, high level of machinability and can also be formed with heat or cold. ***Aluminium 6061 T6 (SS)*** is chosen for this research based on its properties as shown in Table III and Table IV [20].

Table III: The advantages and disadvantages of the PLA and aluminium materials

Material	*Polylactic acid (PLA)*	*Aluminium*
Advantages	Biodegradable, cost-efficient, versatility, aesthetic value (smooth finish)	Corrosion-resistant, lightweight, economical, Strong (Aluminium has the highest strength-to-weight ratio of any metal)
Disadvantages	Brittle, degrade when exposed to heat (glass transition temperature below 60°C)	Sharp edge if not properly cut, lower strength than steel

Table IV: Properties of PLA and aluminium

Properties	*Polylactic acid (PLA)*	*Aluminium*
Tensile strength (MPa)	37	124–290
Density (g/cm^3)	1.3	2.70
Elongation (%)	6	12-25
Young modulus (E) (GPa)	3.5	68.9

E. Computer-Aided Design of the Humanoid Robot Torso

In order to design the humanoid robot torso, Solidworks software is used to draw the 3D model. The location and orientation of the motor is defined and embedded into the design. The design process has been repeatedly improved to obtain the best output.

The initial design for the new humanoid robot torso started with a very basic structural Aluminium frames. The aim is to assemble the arm, head and all motor without any interference to the main structure. The focus of the structural requirement will be on force analysis. Aesthetic value and reduction of excessive design needs to be taken into consideration.

Middle Torso

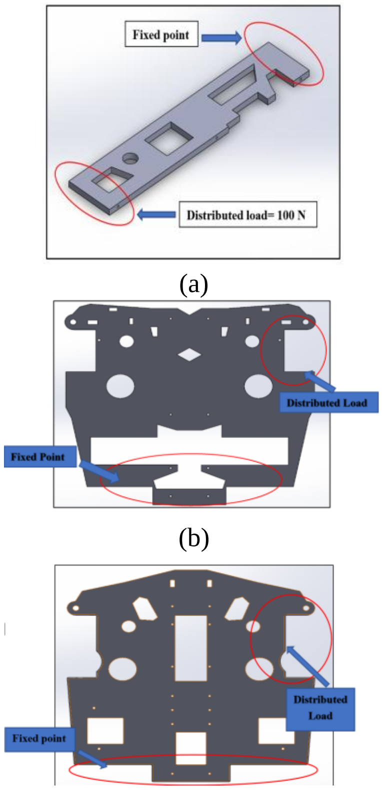
The middle torso is the most important part of assembly since it acts as the support for both front and back torso section. It needs to be designed to integrate well with other parts, as well as to withstand all applied forces. The force applied may come from the torso, arm, the robot head and their servo motor. The joint needs to be aligned carefully in order to successfully assemble the whole torso. The inner part of the middle torso was designed to allow the servo motor placement. Fig 5(a) displays the middle torso design.

Front Torso

For the front torso, the design was inspired by the shape of the human front torso. The torso joint need to be aligned with the arm section, thus, the features cannot be simply modified. Due to the structure of the arm joint and servo motor, some difficulties and structural limitation are evident and needs to be overcome to avoid any malfunction in the design. The final 3D model design of the front torso section is shown in Fig.5(b).

Back Torso

The back torso is the longest frame of the whole structure. It is designed to hold the head and to support the arm joint. The shape is similar to the real human back. The hole's design is made for the servo motor and shoulder alignment. Fig.5(c) shows the back-torso 3D design.



(c)

Fig 5: 3D model of a) middle torso b) front torso c) back torso.

F. Fabrication

The fabrication process started with cutting the raw material. Aluminium had been chosen to be utilized for the torso section. In this research, all three sections has been developed using CNC machining process and waterjet cutting. The middle torso is the most complicated and crucial feature in terms of strength to support the whole arm, head and another parts. Fig 6 shows the finished product of the upper torso humanoid robot.

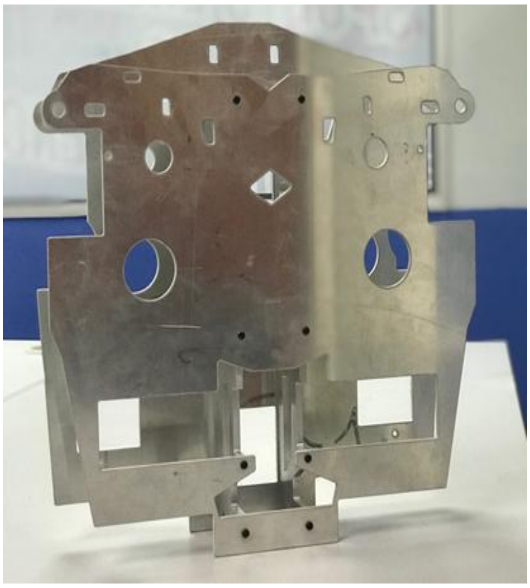


Fig 6: Fabrication process of the upper torso using water jet cutter and CNC machine

III. RESULTS & DISCUSSION

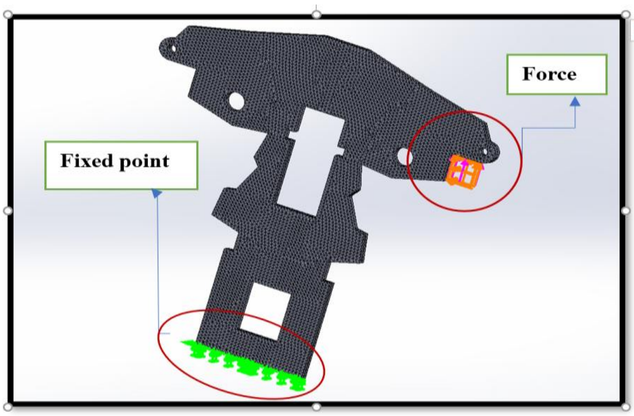
A. Initial Design of Humanoid Robot Torso Analysis

Fig 7(a) shows the 3D model and boundary condition of the initial design. The material used is PLA and the force acted in the y-direction was calculated. The applied force experienced by the torso is 100N [1][14]. The load applied is based on the head, upper limbs part and Arduino component. The fixed point is applied at the base of the torso as shown in Fig 7(a).

The torso experienced deformation due to the force acting and weight of the Arduino component, upper limbs and head. Fig 7(b) and Fig 7(c) show the 3D modelling and result of static analysis of the torso part.

Von Mises Stress Analysis

Fig 7(b) shows the Von Mises Stresses on the torso part. The maximum stress for the part is 1.222e+006 N/m^2. Critical area can be seen at the shoulder joint and the bonded surface where the stresses is recorded the highest. The deflection of the torso when forces (distributed, F = 100N) are applied from below and it is shown in Fig.10. From the analysis, it can be seen that the torso is experiencing the maximum stress at the assemble joint.



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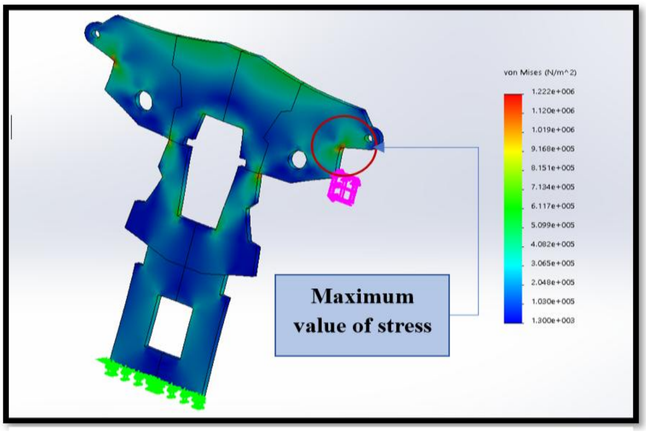

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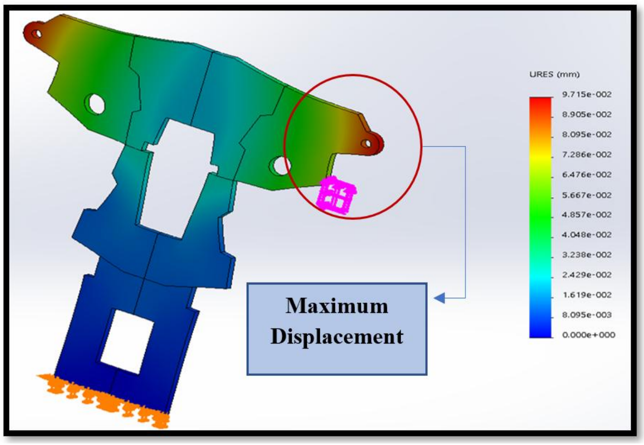


(c)

Fig.7: a) Meshing of the initial design b) Von Mises stress on the torso c) Displacement analysis of the torso

Total Displacement Analysis

Based on the result, the maximum displacement for the section is 9.715e-002 mm. The highest displacement is at the shoulder joint area and its experiences the highest stress due to the upper limbs load and holding the arms (Fig. 7(c)). Based on the analysis, these critical areas are having insignificant displacement since the value is very small (0.09 mm.

Improvement of the Design

From the initial design analysis, the deformation, Von Mises stress and strain act on the torso can be reduced by improving the critical section and proposed a better characteristics material. The improvement is done by replacing the PLA to a higher strength material such as Aluminium. Aluminium is stronger than PLA based on the Young' Modulus and tensile strength. The design is modified and simplified by reducing the component that needs to assemble. However, there are a few areas that cannot be changed and remains constant due to the alignment factor and dimension of the existing part such as an arm section. The joining method used to assemble the part is altered from adhesive to bolt assembly. The dimension of the torso part is tabulated in Table V.

Table V: The dimension of the torso section

Torso Part	*Length (mm)*	*Height (mm)*	*Thickness (mm)*
Front	9	289	3
Back	309	320	3
Middle	57	279.7	5

B. Analysis of the New Humanoid Robot Torso

The middle torso section is the crucial part of the torso that holds the whole upper body, the front and the back torso. A series of analysis had been performed on the section to evaluate the design and its stability under various loading. The static analysis was conducted on the torsos part by using SolidWorks simulation to evaluate the load applied due to gravity for its own mass and another section. In order to do so, the fixed surfaces of the part were selected to create the mesh for analysis.

For the assembly analysis, the key factor is the stability and strength of the torso while undergoing a particular motion or loading. The assembly will undergo deformation due to the forces acted on the part. Based on the analysis generated by the solid work simulation, none of the torso parts undergoes critical deformation or failure. The boundary conditions needed to be stated before doing the analysis. Fig 8(a) shows the force act to the torso in the y-direction and the value force applied is 100 N. It is also illustrated that the fixed point was applied to the bottom section of the torso.

Fig 8(b) and Fig 8(c) shows the analysis of the humanoid robot torso assembly part. The torso will deform due to the force acting on it. The weight of the arm and head affect the deformation value.

Von Mises Stress Analysis

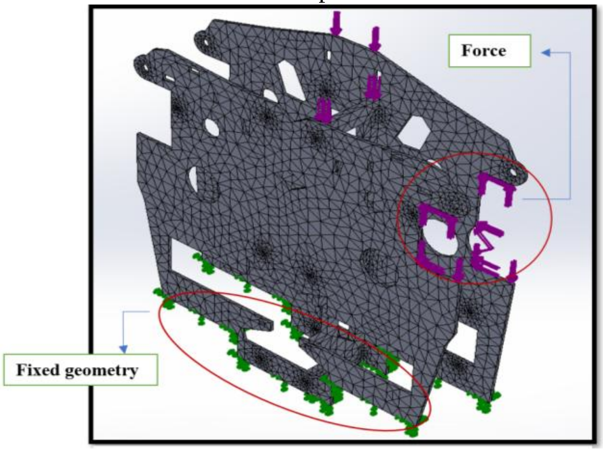
Fig 8(b) shows the Von Mises Stress analysis of the improved torso design. The maximum stress of Von Mises stress before the improvement is 1.222e+006 N/m^2 while after improvement is 7.621e+006 N/m^2. Although the stress value after improvement is higher, the maximum yielding strength is increased and can withstand higher applied load compared to initial design. Thus, based on the material properties of Aluminium, the new humanoid robot torso is much stronger compare to the initial design. Referring to Fig 8(b), there are several critical areas located at the arm joint area, however, the critical area does not affect the torso overall performance or structure due to the small value of stress. The analysis below shows a lot of blue area which indicates its overdesigned. Even though the new humanoid design is much stronger, the overdesign feature is not ideal and need to be improved in near future due to the costing factor.

Total Displacement Analysis

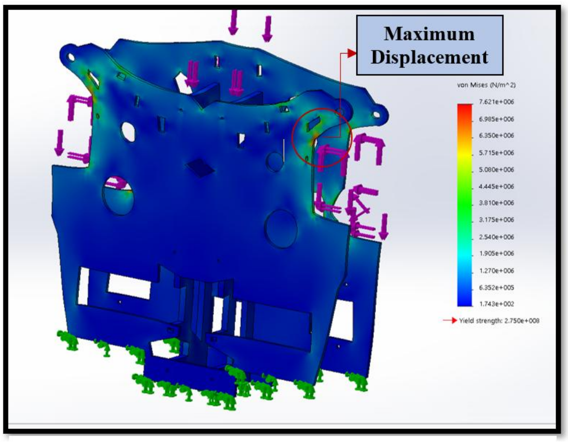
The total displacement of the torso is shown in Fig.8(c). Based on the results, the maximum displacement for initial torso design is 9.715e-002 mm while after improvement is 6.783e-003 mm. The percentage is decreased by 30.18 %. The reduction of displacement value is small and insignificant. The displacement value is reduced due to the simplified design, material changes which is Aluminium and the reduction of the assembly joint. The maximum value of the displacement can affect the structure of the torso, hence, contribute to failure.

From the analysis of the torso, it shows that the design is compatible with the arm joint and head. The design has not hindered the movement of the arm and head motion. Therefore, the upper limbs and the head part can rotate and move with ease. The simplified design is stronger than the initial design. Based on the design performance, the torso part is strong and stable enough to withstand the upper limb and head weight compared to the initial design. The deformation illustrates in the simulation show that the design can hold 100 N force without experience failure.

The design was improved from an initial design by modifying a few changes such as choosing suitable and lighter material and alter the design to one-piece part. For this project, Aluminium was chosen due to its strength and easy to machine compared to PLA. A defect can occur in the 3D printing by using PLA material. The 3D printer specification usually limited to a small part. Besides, Aluminium is easy to fabricate and can be built to any shape. The selection of materials must be right before the development and fabrication process. This is to make sure the torso will not fail due to the force and stress act upon it.



(a)



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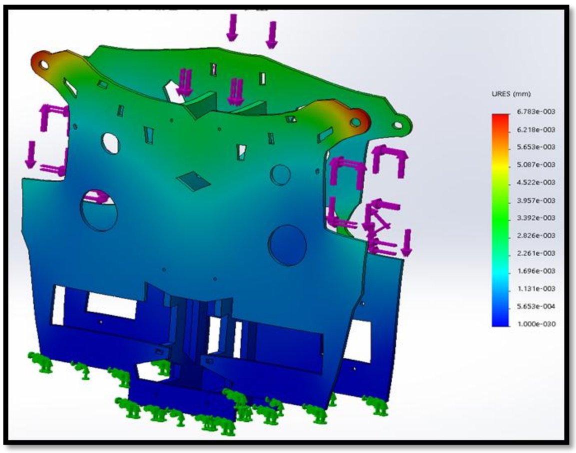

(c)

Fig 8: a) Boundary condition for the torso assembly part (b) Von Mises Stress acting on the torso c) Torso displacement analysis

IV. CONCLUSION

A new torso structure for humanoid robots has been proposed based on the initial design and human appearances. The proposed system with 1 DOFs shows high strength and easy-to-control features. The humanoid robot torso optimization design based on initial design has been implemented for better motion performances, strength and stability. A 3D model has been elaborated and simulated in SolidWorks for static analysis. From the experimental design and the model, it shows that maximum Von Mises Stress and maximum displacement are achieved at 7.621e+006 N/m^2 and 6.783e-003 mm respectively. The result from the finite element analysis indicates that the new torso humanoid robot design which uses common material such as aluminium shown an increment of 523.65% in Von Mises Stress analysis and 30.18 % percentage decreased in displacement value. In terms of strength (based on the finite element analysis), the new humanoid robot torso is stronger compared to the initial design. Also, the mass of the new torso is heavier compared to the initial design using PLA material. It is also proven that the simplified design is the best option to increase strength and stability since the aim of this study is to find the optimum condition that can increase strength and reduce the time and cost of the fabrication of the torso part. By reducing the joint and simplifying the design, the optimum condition for better torso performance can be achieved.

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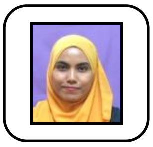

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