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ORIGINAL ARTICLE

Development of Walking Robot Using Compliance Mechanism

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ABSTRACT – Walking robot is a trend in this 21st century as Industrial Revolution 4.0 which involved automation has become a hot topic. Unlike ordinary moving robots, walking robots that take humans and animals as references can move on unpaved surfaces. Compliance mechanism is a flexible mechanism that transfers input force into output force through plastic deformation of certain members in the structure. A compliant structure can be classified as a monolithic structure that deforms elastically without any joint or linkage between the members. Unlike motorised robot legs requiring an input motion in each joint and link, a single input force can operate a compliant leg. Therefore, this research aims to develop a 3D printed compliant leg. This project is challenging because there is no reference for the single-piece compliant leg development using Three-Dimensional(3D) printing technology. The application of Jansen Linkage in the development of the compliant leg also results in difficulties because there is no standard equation for the calculation of each member in the Jansen Linkage. Hence, the development of the Jansen Linkage using different dimensions will solve these problems by varying the difference occurring upon changing the dimension. We also make Finite Element Analysis (FEA) of the product. The thesis will be supported by the walking motion pattern, force vs time graph and FEA analysis results for the product.

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INTRODUCTION

Compliance mechanism is a high flexibility mechanism that transmits motion and energy through elastic deformation of the structure. The compliance mechanism is widely used in the robotics field as a linkage between two structures despite its adaptability to various mechanisms. According to (De Gruyter, 2019), the compliant mechanism can be classified into two major classes, a fully compliant mechanism that motion occurred only due to the compliant structure and a partially compliant mechanism that motion of compliant structure driven by a rigid-body point. A complaint joint is a single point in a specific localised area that connects two members in a degree of freedom (DOF) point [1]. The continuous research on compliance mechanisms has developed compliant actuators and sensors that applied compliance mechanisms to their working principle.

A compliant leg is a mechanism that imitates the locomotion of humans and other species in movement using the characteristic of the compliance mechanism. The flexibility and adaptability of compliant leg grant a great advantage to be applied on the moving mechanism on different terrain. A compliant leg designed for landing purposes was presented [2]. The compliant leg is built up with a 3D printed member a spring is attached for the compliant purpose. The impact absorption of the compliant leg enhances the chance of landing up to 73% compared with the active damping system (45%). It absorbed the excess damping force through elastic deformation of the spring and transmitted it into elastic energy for the retraction of the spring. The height of the dropping point is fixed due to the spring's stiffness and can be increased when using a spring with higher tensile strength and Young Modulus values.

3D printing has a great advantage to minimise the cost despite its raw material, Polylactic acid (PLA) filament. PLA filament is a vegetable-based plastic material that is biodegradable. The production cost of PLA filament is cheap despite its accessible obtained raw material. Research has developed a 3D printing replica with the same function where the fill density of the replica is adjusted and test with the Ansys software to obtain the best parameter of the design that can sustain the weight of the load [3]. The 3D printed replica has the same principle of mechanics as the real-life product. The replica can be easily disassembled and reassemble due to parts by parts production using 3D printing.

RELATED WORK

In the paper by Federov et al. [4], compliant leg obeys the characteristic of the compliance mechanism in adaptability. The elastic properties of compliant leg grant flexibility on a different surface. A rigid leg replica can be constructed using a compliance mechanism into a compliant leg. The flexibility of the compliance mechanism can imitate the motion of the gears in the rigid legs. The compliant structure proposed by Federov replace the force transmission from mechanical

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energy to kinetic energy using gear into a compliant structure that transfers the force from elastic energy to kinetic energy. Unlike rigid leg, the compliant leg can deform to adapt to different terrain with the same moving pattern. The research also shows the distribution of stress in different locations upon the compliant leg step on it. A constant input force is required to fully operate a compliant leg upon the different surfaces of the testing plane. A higher input will produce upon walking through the big obstacles to maintaining the angle of the body for stability. The retraction of the compliant leg enables it to move at different heights while maintaining the robot's stability. The compliant structure tends to deform and retract back to its original position after a complete cycle.

A compliant leg that emphasises applying the compliance mechanism in the knee joint of a robot was introduced [5]. The knee joint is the transition point for converting rotational energy to kinetic energy for a moving motion. A knee joint compliance mechanism can help convert the rotational energy to kinetic energy with minor loss during the process. The compliant knee joint's elastic deformation can help store energy transmit into it then transfer to the adjacent structure. The application of a compliance mechanism in the knee joint can also strengthen the structure. The elastic properties of the compliant knee joint can reduce the damage on it as the energy is transmitted through an elastic deformation but not a direct transmission like gear. The compliant knee joint also reduces the planar force exerted on the whole structure, justifies its ability to support when the structure is in motion.

In the paper by Sun et al. in 2016, the compliant legs can perform a similar gait pattern with human legs movement [6]. Its adaptability grants researchers an advantage to perform different control methods on a compliant-based robot to achieve a high efficiency simple moving pattern. A study also discusses the possibility for a bio-inspired robotic leg to be constructed using 3D printing [7]. For a bio-inspired robotic leg, a compliant structure is always applied in the construction. The ability of 3D printing to create a structure with a compliance mechanism has been investigated. It was found that by changing the fill density of the compliant parts, the product can exhibit an identical characteristic. The product has sufficient tensile strength to carry its weight and to withstand the force exerted on the contact surface.

A compliant leg has been categorised into a fully compliant leg and a hybrid compliant leg. Both applied compliance mechanisms at the joint and linkage of the leg structure where hybrid compliant leg combines compliant structure with the stiff mechanical structure. A study shows the relation between the compliant leg and the stability [8]. Different leg structures can obtain similar output and walking patterns in steady-state walking from the compliant system. Besides that, the ability to resist perturbation from substratum vary when the different compliant leg is applied. The pure models have inherited passive stability from the legs for a hybrid compliant leg, reducing the active control acting upon it. The adaptability of the compliance mechanism enables it to be applied together with a different mechanism and different contact surfaces.

METHODOLOGY

This research is about the development of the compliant leg for the walking robot. A series of consideration and calculations, as in Figure 1, must be done to develop a compliant leg for a walking robot. An initial concept of the compliant leg needs to be determined. The degree of freedom (DOF) needs to be determined, and the compliant leg's initial design needs to be constructed. The design is then modified into a one-piece product with the exact specification and function. And eventually, the final product will be developed based on a modification of the previous product. The process begins with developing a 2D compliant leg, followed by developing a 3D printing compliant leg, then into the analysis of the product and finally product fabrication. For product analysis, the walking motion and FEA will be considered to decide the ideal product.

Development Process

The first step of development requires the verification of the foundation idea of the product. In this research, Jansen linkage will be the foundation idea to develop the compliant leg. Jansen linkage is an eleven-bar mechanism that is crank driven and mimics the motion of the leg. Therefore, a series of different parameters of Jansen Linkage will be constructed and demonstrate its walking motion. The simulation test follows the process. The walking motion of each parameter will be taken into consideration upon the selection of the best parameter. FEA will also be conducted between the final product and the Holy Number compliant leg. The evaluation on different aspects like Von Mises stress, equivalent strain and static displacement plot will be conducted to compare the performance between the two parameters.

After the evaluation is done, the fabrication process will then start. The design of the 3D printed product will be based on the dimension of the best performance obtained from previous simulation results. The linkage and joint will change to a 3D printed structure that connects all other parts into a whole piece structure while remaining its function to deform and transfer the energy to the relevant structure. Since the product will be a 3D printed product, other parameters like the thickness and width of the products should also be considered. Since the design of each member will be bar shape, the dimension of the whole structure will also alter, but the connection length between each member will remain the same.

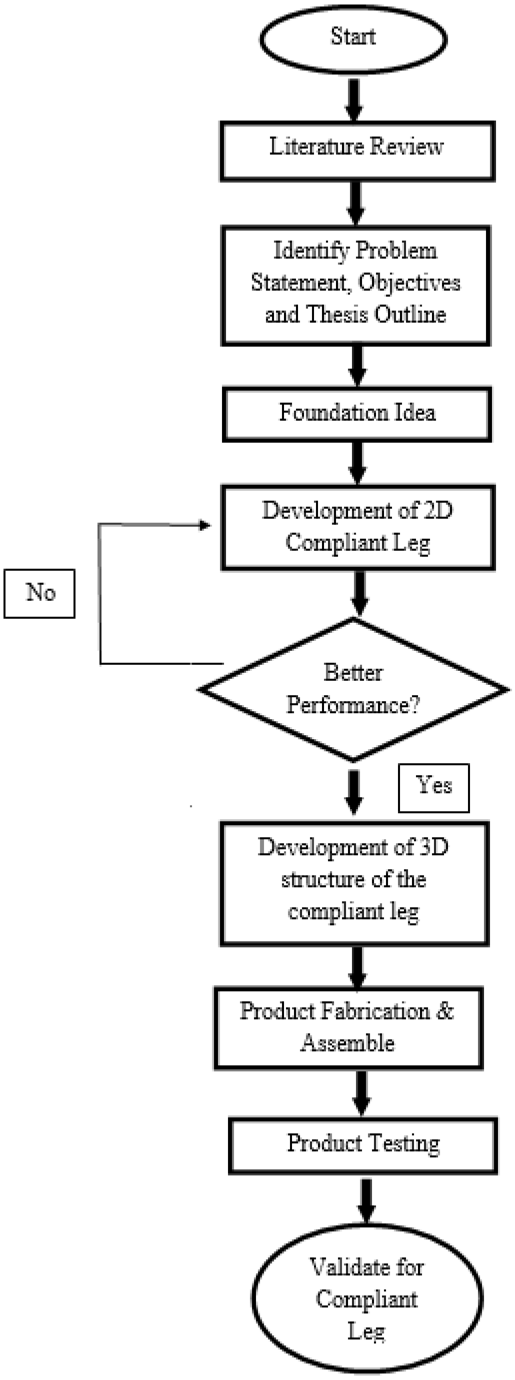
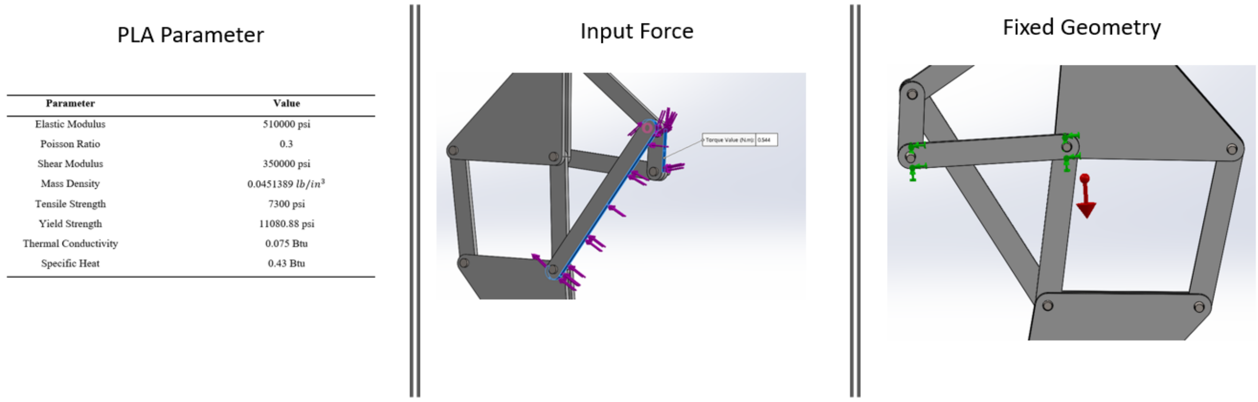


Figure 1. Process Flowchart

Table 1. Dimension of Different Parameter

Members	Parameter 1 (mm)	Parameter 2 (mm)	Parameter 3 (mm)	Parameter 4 (mm)
A	15.2	28.0	25.0	22.4
B	16.6	14.7	11.4	6.9
C	15.72	18.9	13.2	10.4
D	16.04	12.0	13.0	7.8
E	22.32	17.7	17.3	17.7
F	15.76	13.3	14.7	13.3
G	14.68	13.0	15.5	9.2
H	26.28	27.1	25.3	14.9
I	19.6	25.4	20.0	11.8
J	20.0	30.6	25.2	24.6
K	24.76	30.4	27.6	22.5
L	-	2.2	0	1.5
M	6	6.5	8.5	5.0



Parameter	Value
Elastic Modulus	510000 psi
Poisson Ratio	0.3
Shear Modulus	350000 psi
Mass Density	0.0451389 lb/in^3
Tensile Strength	7300 psi
Yield Strength	11080.88 psi
Thermal Conductivity	0.075 Btu
Specific Heat	0.43 Btu

Figure 2. Fixed Variable on FEA

Experiment Parameter

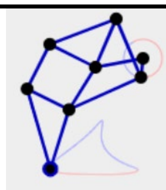
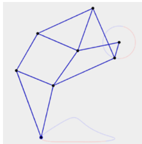
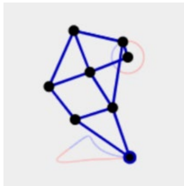
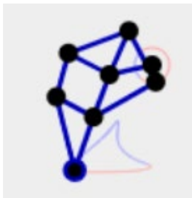
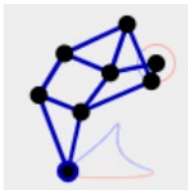
There are a few variable parameters and measured parameter in this experiment. The parameter that we able to set is the dimension of the product. The dimension is vary so that different walking motion will be produced. Besides that, the dimension of the structure also affect its performance in FEA.

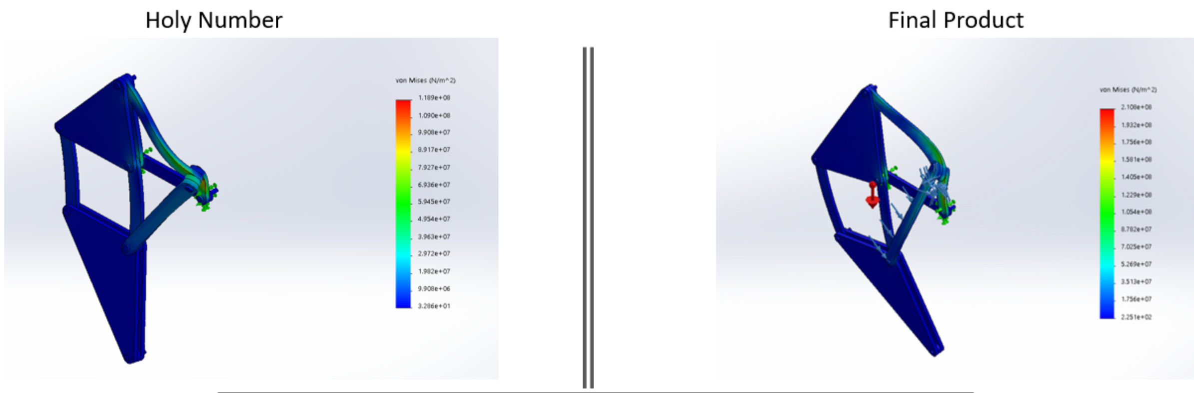
The measured parameter in this experiment walking motion, Von Mises stress, equivalent strain and static displacement plot. Von Mises stress is a value applied by engineers to determine whether a model will fracture or yield. Von Mises stress is often applied for ductile model. Von Mises yield criterion states that a model will yield if its von Mises stress under a load is equal or greater than the yield limit of the model with tension applied on the model. Equivalent strain in FEA is another values applied by engineers to analyse the performance of a model. Unlike von Mises stress, equivalent strain emphasise the deformation of the element inside a model. The strain of a model is highly dependent to the factors like elastic limit, upper and lower yield, and rupture stress. Elastic limit defines the region where the energy is still stores inside the model during stressing and straining process. When a model reach a critical point in plastic range, it is called upper yield limit. The lower yield limit is the lowest point after the model reach the critical point. Rupture stress is the separation of an object caused by stress which fracture occur. Static displacement plot while indicates the dimension of deformation of the product in certain region. The value is compared with a list of table to find ou the total displacement occur in the structure.

EXPERIMENTAL RESULTS

The evaluation will conclude the results such as walking motion of different dimension of the compliant leg, and FEA results on different aspect. The evaluation will take place on Holy Number compliant leg and self-constructed compliant leg. The performance of two models on different aspect are meant for comparison to gain better understanding against the behaviour of compliant leg and determine the best model to be developed. The real product will also be presented in this chapter. All the parameter involved in FEA will also be discussed and shown in this chapter. The results on different aspect of the compliant leg will be discussed and compared among two model to conclude the better model produced in this project. The product will be tested for its locomotion at different angle to identify its function as a compliant leg.

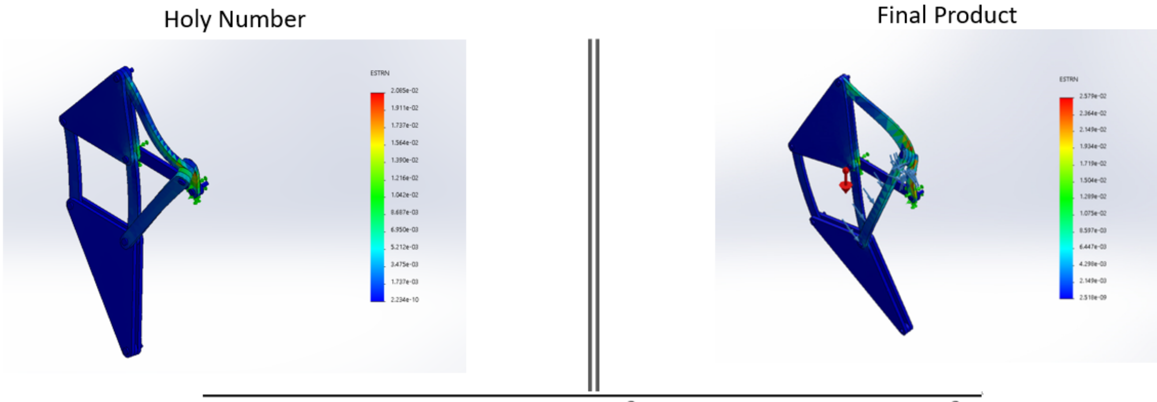
Table 2. **Walking Motion of Different Parameter**

Parameter	Walking Motion
Holy Number	
Parameter 1	
Parameter 2	
Parameter 3	
Parameter 4	



Model	Minimum (N/m^2)	Maximum (N/m^2)
Holy Number	3.286e+01	1.189e+08
Parameter 1.2	2.251e+02	2.108e+08

Figure 2. Von Mises Stress Results on Both Model



Model	Minimum (N/m^2)	Maximum (N/m^2)
Holy Number	2.234e-10	2.085e-02
Parameter 1.2	2.518e-09	2.579e-02

Figure 3. Equivalent Strain Results on Both Model

Model	Minimum (N/m^2)	Maximum (N/m^2)
Holy Number	1.00e+00N	3.813e+00
Parameter 1.2	1.00e+00N	4.380e+00

Figure 4. Static Displacement Plot Results on Both Model

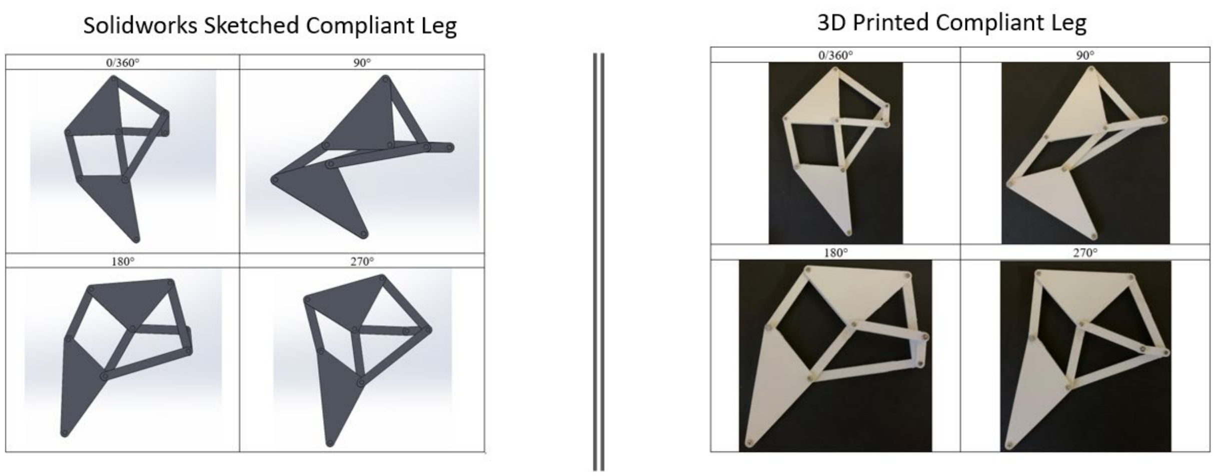


Figure 5. Locomotion of Both Model At Different Angle

Table 3. Difference Between 2 Models in FEA

Parameter (Maximum Value)	Difference Between Final Product and Holy Number (%)
Von Mises Stress	77.29
Equivalent Strain	23.69
Static Displacement Plot	14.87

Result and discussion

From above table, we can observe the walking motion of each parameter. Holy Number compliant leg has a smooth contact point with the surface. In this instance, less resultant force will acting on the compliant leg preventing it from damage. However, the walking motion has a sharp corner when the compliant leg is lifted and extended to maximum. This will results in a rapid changes of the rotational speed at that point and increase the friction between the bar and eventually cause wear at the bar.

From Table 1, Parameter 1 shows the same smooth contact point with a larger contact area to the surface. A larger contact area means that the contact time of the foot and the ground is longer thus it will results in a wider forward movement, resulting in a greater travel distance. When the leg is lift up and extend, is also results in a smooth corner resulting a smoother motion which cause less damage to the compliant leg. For Parameter 2, it also shows a smooth walking motion. However, its walking motion upon touching the ground shows an inclined line. This indicates that the compliant leg will be lifted earlier. Furthermore, the red line which indicates the contact of the compliant leg with the ground in Parameter 2 is starts earlier before the flatten surface. This indicates that the compliant leg will be in contact with the ground before the leg is fully extended and eventually cause unstable to the structure.For Parameter 3, it shows a similar walking motion like Holy Number compliant leg with shorter contact area. Parameter 4 while shows an exact similar walking motion pattern like Holy Number compliant leg. This indicates that both Parameter 3 and 4 has same defect as Holy Number leg.From above discussion, we can conclude that Parameter 1 is the most suitable parameter as the dimension of our product as it results in a greater contact surface and smoother walking motion when compare with Holy Number compliant leg.

From Figure 2,Parameter 1.2 results in a better performance than Holy Number compliant leg. Parameter 1.2 compliant leg has greater values of von Mises stress in both minimum and maximum value. Results shows that Parameter 1.2 can withstand a higher force exerted on it before deformation and fracture occur. Von Mises stress can be describe as the force acting on the surface of the model. The effect of the stress occur on the surface element of the model initially then gradually into the internal element of the model. In this instance, Parameter 1.2 has a higher withstand power towards the outside force which direct acting on the surface of the model. Under the same gradually increased forces applied on both models, Holy Number compliant leg will deform and fracture earlier than Parameter 1.2 as it has a lower withstand power.

From Figure 3, Parameter 1.2 results in a better performance than Holy Number compliant leg. Parameter 1.2 compliant leg has greater values of equivalent strain in both minimum and maximum value. Equivalent strain can be describe as the force to deform the internal element of a model. The equivalent strain only involved in the region where the force is executed. When the model starts to deform, the internal element of the model will starts to experience forces. Results shows that Parameter 1.2 can withstand a higher force exerted in the internal element of the model before fracture occur. In this instance, Parameter 1.2 has a higher flexibility as its internal element can withstand a greater force exerted on it when compared to the Holy Number compliant leg. Under the same gradually increased forces applied on both models, Parameter 1.2 has a higher deformation range than Holy Number compliant leg.

From Figure 4, Parameter 1.2 results in a better performance than Holy Number compliant leg. Parameter 1.2 compliant leg has greater values of static displacement plot maximum value. Noted that both models have the same minimum values. This is because the material properties of both models is same. Static displacement plot is the maximum displacement a model can withstand before fracture. Parameter 1.2 compliant leg has a better results because it has a larger dimension. When force exerted on it, it can store and withstand a larger force than Holy Number compliant leg. So, under a same and gradually increased force, both model will deforms but Parameter 1.2 compliant leg will have a greater range of deformation which makes it more durable than Holy Number compliant leg.

From the FEA results, it is clearly that the Parameter 1.2 compliant leg has a better performance than Holy Number compliant leg. It can withstand a larger force before deforms and fracture.

From Figure 5, we can see that the motion of the 3D printed compliant leg is same with the Solidworks sketched compliant leg. On 0/360°, the 3D printed compliant leg also remain in a rest position with a contact on the ground. On 90°, the 3D printed compliant leg has been lift up and the contact point will move forward providing an initial force for the forward motion. On 270°, the foot of the 3D printed compliant leg is extended to maximum and begin moving downward. In this instance, same like the sketched compliant leg, the drag force and friction on the foot with the ground will provide a force to the compliant leg to move forward for a fixed distance and finally back to its rest position.

From results above, we acknowledge that the Parameter 1.2 compliant leg has a better results in FEA when compared to Holy Number compliant leg.From Table 3, we can determine the difference between the values of each Parameter in FEA. For Von Mises stress, the value of Parameter 1.2 compliant leg is 77.29% better than Holy Number compliant leg.

For equivalent strain, Parameter 1.2 is 23.69% better than Holy Number. For static displacement plot, parameter is 14.87% better than Holy Number. From the values above, it is clearly states that Parameter 1.2 compliant leg has a better performance than Holy Number compliant leg.

CONCLUSION

This report has discussed the development of a compliant leg for a walking robot. This research was conducted to design a compliant leg for walking robot using 3D Printing technology. Then, the comparison between the Holy Number compliant leg with the Parameter 1.2 compliant leg to indicate a better model as the compliant leg. Lastly, fabrication of product is conducted.In this project, there are 4 major steps required to develop a compliant leg which is 2D development of 2D compliant leg, development of 3D compliant leg, product analysis and product fabrication. The first 3 steps is essential to develop a compliant leg as it indicates the performance and motion of the compliant leg. Hence, the compliant leg is tested for its walking motion and FEA. From the simulation results, Parameter 1.2 compliant leg shows a better performance than the Holy Number compliant leg. Parameter 1.2 results in a smoother walking motion and higher force upon acting on the ground. The Holy Number compliant leg also results in a good performance too but Parameter 1.2 compliant leg exceed its performance. For FEA, Parameter 1.2 results in a greater Von Mises stress sustainability, greater equivalent strain sustainability and finally higher tolerance of static displacement plot when compared to Holy Number compliant leg. The results shows that Parameter 1.2 can withstand a larger force applied on it before fracture.

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