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Non-Invasive Invitro Modelling and Finite Elemental Analysis of a Uniquely Designed Prosthetic Hand

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Abstract: In the presented work a unique design for the upper limb prosthesis is evaluated for the stress concentration by the help of finite element analysis method. This paper gives validation for the novel prosthesis design. Human hand is most difficult body part to mimic both aesthetically and functionally. To obtain a functional prosthesis studying stresses developed in the most functional parts of hand prosthesis is mandatory. A static 3D structural finite element approach was followed. This study gives overall distribution of stress on the tendon, pulley and palm being the maximum force exerting parts. Thus, design efficiency is validated and fabrication of said hand is done using 3D printing. Fabrication of the prosthetic hand has been designed with the safe limits of factor of safety and have been designed for a maximum of weight lifted of 0.5 kg and it is tested safe as per finite element analysis.

Keywords: Finite Element Analysis, Prosthetic Hand, 3D – Printing, Biomedical Devices, Fabrication

1. Introduction

Upper-limb amputations can be disturbing psychological, bodily and socio-economic shock to the patient. The amputee has to take help of the prosthesis to do daily life activities. In India the cost of a modern prosthetic arm is quite high[1)]. Low-cost prosthesis functions are comparatively lower than those which are moderately or high-priced devices [2)]. Prosthesis such as the I-Limb and the Be Bionic prosthetic hand function using independently actuated fingers and are also capable of number of grips[3)]. But, the costs linked with these prosthetic hands can majorly be taken advantage of this revolutionary technologies only if the amputee is funded.

Hence, there is a clear shortage of affordable, high functionality equipments in the upper-limb prosthetics marketplace of developing countries [4)]. The aim of this paper is to address this shortage by designing and fabricating a 3D printed prosthetic hand that has comparable functionals to the most exclusive prosthetic hands offered at a cost intensely lesser prices.

Clement et al., said that human hand is capable of realizing that a large number of difficult movements that brings the capability to intermingle in the surrounding and connect with people[5)]. El Kady et al., presented that upper limb loss may give rise to physical as well as psychological illnesses to an amputee[6)]. In last 30 years various prosthetic hands were developed[7)]. There are mostly three kinds of prosthetic hands existing for those who suffer from any kind of amputation or any by birth lackings[8)]. Otto Bock hand® are very famous and sturdy which allows to apply a maximum amount of force 100 N and it offers only 1 (DOF) degree of freedom that weigh upto 600 g[9)]. The human hand has total of 22 DOF along with a maximum tip force that can be exerted is 500 N though most daily routine actions require fingertip forces below 70 N[10)], and having average weight 500 g[11)].

Cipriani et al said that numerous prosthetic hands have been developed like the one that is being shown[12)] that are having 16 DOF as well as operated with 4 electrical motors, weighing 530 g and ability to lift 10 kg. Various types of actuators and transmission systems have been used in order to achieve the movements given in the Kargov et al. [13)] that use hydraulic pump along with valves as actuators [14)]; rack and pinion system was taken for its proposal. The developments in design, anatomy and technological advancements have made important aids in the evolution of aesthetic and design of the prosthesis in last decades, also this has permitted a improved method to replicate the movements and mechanics of a normal human hand. Pérez et al. said a hand prosthesis prototype can be developed by computer tomography (CT) scan got from the normal hand of amputee[15)]. Analytical as well as experimental models in the biomechanics gives important data that gives the better understanding of the behavior of diverse systems subjected to mechanical loading conditions[16)]. The (FEM) finite element method, makes probable to calculate stress distribution and strains, that can be difficult to get through experimental or any analytical methods. Bougherara et al. have given many example of biomechanics using FEM (2009) and Omasta et al. (2012) presented the stress distribution in a lower limb prosthesis and also in trans-tibial prosthesis, respectively. Ansys ® Workbench was used to get the results in this study . Geng et al. (2008) presented the use of FEM in dental field[17-19]. Stanciu and Stanciu presented a study in which the (FEM) finite element method in the hand prosthesis that is hydraulic actuators based[20]. That analysis was done using the cosmosworks ® and was accomplished in two positions, first for the hand that is wide open and the other for an midway position. A 10 N of load was taken and applied on fingertip of the middle finger. Every finger was having same construction so analysis was done on only single finger.

The design and the analysis of a prosthetic hand that is activated by the muscle wires is given in O'Toole (2007) [21]. Device that grips wire was studied and the ideal thickness of the finger wall is calculated by FEM. The anthropomorphic design of the end effectors is shown in Ohol and Kajale (2009) [22]. By using the softwares like ANSYS ® and FEM mostly parts are designed and analysed. Jung and Moon (2008) [23] presented static analysis to find out the finger tip force. Kargov et al. presented a comparative study of the fingertip force distribution among a human hand, a non-adaptative and adaptative prosthetic hand[24]. In this paper the mathematical simulation of stress distribution in the parts of the hand prosthesis both in the cylindrical and precision grasp has been made.

Sharma et al paper gives a study on three-dimensional stress distribution, with minimum detrimental effects to natural human joint. The discussed design in the paper is also experimentally validated and also helped in analyzing medical consequences for real temporomandibular joint surgery[25]. FEM is an effective tool for structural analysis, saving time and cost of manual testing in the laboratories[26].

The intricate design requires much time in the conventional machining process as compared to the same may be done simply 3-D printing technology with lesser time[27]. PLA (polylactic acid) and PETG (polyethylene terephthalate glycol) have been widely used in the medical industry, automobile industry, packaging industry, aerospace industry etc. due to its biodegradable nature[28]. There are two types of prosthetics namely active[29] and passive[30]. Passive refers to a prosthesis which is aesthetic only where as active means having functionality[31]. The prosthesis needs to be dynamically and statically stable[32]. The prosthesis is made considering all design aspect in consideration.

2. Design and fabrication

2.1 3-D modelling

This paper talks about a prototype which is based on human hand anatomy. The human hand is made up of bones in the form of fingers. These bones are called phalanges. Each fingers is built of four phalanges namely distal, middle and proximal phalanges and metacarpal bones[33]. The movement of fingers (flexion or abduction) is done with the help of tendons and ligaments. In the prosthetic hand tendon is used for this movement which allow each finger for one degree of freedom (DOF). The control of prosthetic hand is done by the ArdinoUno 2560 and being driven by three stepper motor. It is being battery operated and controlled on/off by push buttons. Solid model of all hand components was made using Solidworks software, the middle, index, pinky and ring fingers are made up of a distal phalanges, medial phalanges and proximal phalanges, that are joined to the palm of the hand as analogy to human hand[34]. The thumb consists of only two phalanges but mounts on a elevated structure away from palm, allowing it for a better grasp. Figure 1 shows 3D CAD Model of hand in closed position and Figure 2 shows the dimensions of hand.

Fig 1: Hand in closed

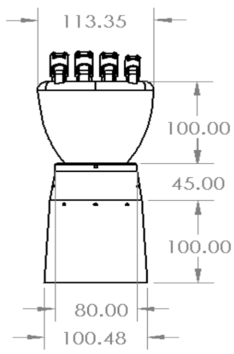

Fig 2: Hand with its dimensions

2.2 3-D printing

The model was then imported to the 3D printing software Cura, then inserted in the printer and fabrication was done. Rapid prototyping was selected as the process for fabrication of the hand on a Fused Deposition Modeling(FDM) 3D printer. All the fabrication details are given in Table no 1. The material used was PLA. This is the most common printing material. Polylactic acid is a bio plastic and thermoplastic made from natural materials. PLA is widely used in other production contexts due to its unique properties and has a great printing performance. PLA offers a toughness of 16.2 kJ/m^2 and its ultimate tensile strength is 26.4MPa[35]. All the properties taken in account while printing is given in Table no 2. Also, PLA doesn't require a heated bed, enclosure or direct drive extrude and is widely available. PLA is quite tolerant of varying print setting and can be printed more quickly than other materials [36].

Table 1: Fabrication Details

Infill	40% grid
Layer height	0.24 mm
Support	Yes
Raft	Yes
Colour	White

Table 2: Selected Material Specification

PLA SPECIFICATION	
TENSILE PROPERTIES	
Toughness	16.2 kJ/m2
Tensile Modulus	2.3 GPa
Ultimate Tensile Strength	26.4Mpa
Tensile Strength at Yield	35.9 MPa
3D PRINTING PROPERTIES	
Expected Max Linear Printing Speed	90mm/s
Hardness	95D
Density	1.24 g/cc
THERMAL PROPERTIES [37]	
Heat Deflection Temperature	49 C
Coefficient of Thermal Expansion	41 x 10-6 m/m·K
Heat Capacity	1,800 J/kg·K
Thermal Conductivity	1,800 J/kg·K

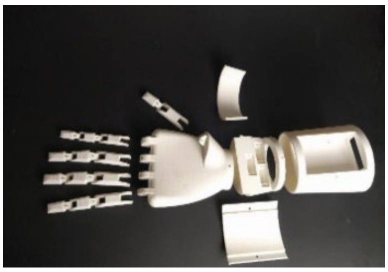

Fig 3: Final 3D printed prosthetic hand

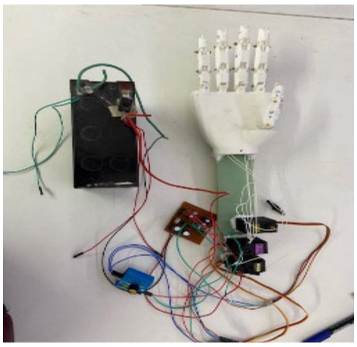

Fig 4: Assembled 3D printed prosthetic hand

Figure no 3 shows the final 3D printed prosthetic hand and also figure no 4 shows the assembled hand which is ready to use.

2.3 Analysis of prosthetic hand

Solidworks® modelling was used to make 3D model of hand. Then mesh generation of the model has been done using solid mesh model. This technique provides much accurate results and regulates the association between the elements[38]. This model generated 10040 number of nodes and 5007 numbers of elements. After the completion of model design then it is being imported in the ANSYS® workbench software for its finite element analysis (FEA). For a particular loading condition, Finite element analysis helps to determine different types of stresses, strains and deformations[39]. FEA is a numerical technique which is used for analysis and modelling of any structure by dividing the structural parts into small finite elements[40]. Boundary conditions taken for the analysis are fixed support. The von-mises stress, deformation and elastic strain are being calculated here for the palm part of the hand model of the prosthetic hand and deformation and that is being compared with those available in literature of 3D printed prosthetic hand.

Table 3: Simulation Study Results

STUDY	TYPE	MIN VALUE	MAX VALUE
STRESS	VON MISES	0.000 MPa	0.826 MPa
STRAIN	EQUIVALENT STRAIN	0	0
DEFORMATION	EQUIVALENT DISPLACEMENT	0 mm	0.020 mm
FACTOR OF SAFETY		5.9	12.071

Table 4: Simulation Study Results

STUDY	TYPE	MIN VALUE	MAX VALUE
STRESS	VON MISES	0.0021 MPa	28.925 MPa
STRAIN	EQUIVALENT STRAIN	0.000031	0.011
DEFORMATION	RESULTANT URES	0 mm	0.165 mm
FOS		1.382	19.033

Table 5: Simulation Study Results

STUDY	TYPE	MIN VALUE	MAX VALUE
STRAIN	EQUIVALEN T STRAIN	0.00038 7	0.00049 2
STRESS	VON MISES STESS	64.423 MPa	115.78 MPa
DEFORMATIO N	URES	0 mm	0.0283 mm
FOS		1.786	3.067

The analysis has been done by the help of FEA in the ANSYS® workbench by the application of compressive loads, the maximum and minimum von-mises stress, deformation and strain for the designed prosthetic hand model are calculated by using various failure theories. In the analysis process, the red colour is symbolic of maximum value for stress, strain and deformation and the blue colour signifies the minimum value. When the load is applied, the maximum equivalent von-mises stress is observed as 0.826 MPa and 0.00 MPa minimum von-mises stress shown in figure 5. The maximum equivalent elastic strain for palm load application as shown in figure 6 observed as 0 . While applying the compressive force, the palm portion is less deformed by a value of 0.02 mm

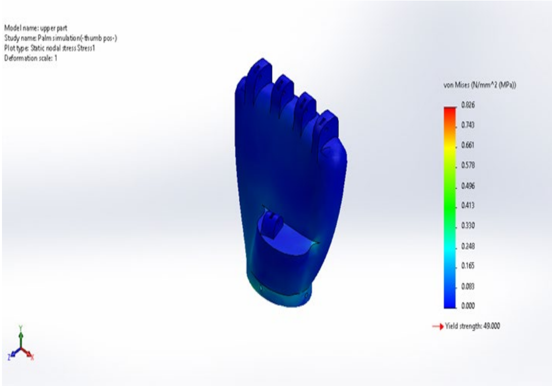

Fig 5: Stress analysis

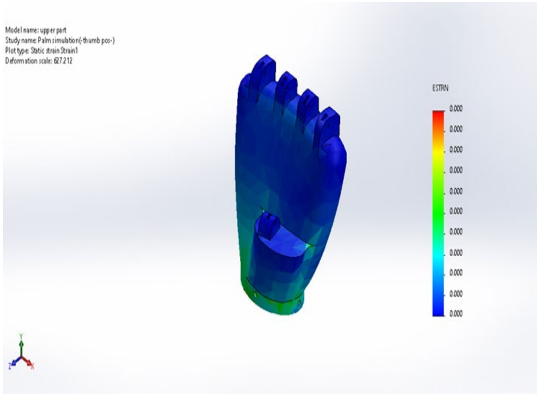

Fig 6: Strain analysis

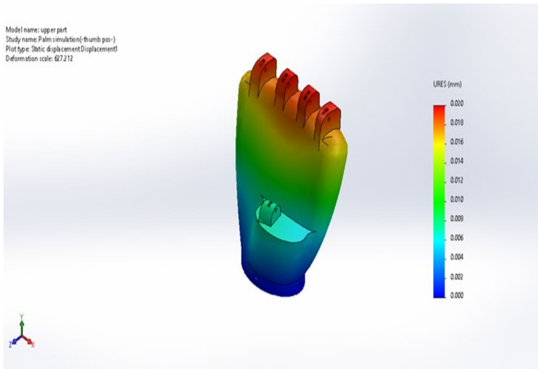

Fig 7: Deformation Plot

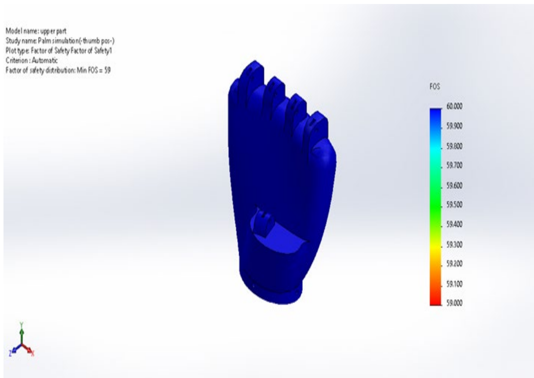

Fig 8: FOS Plot

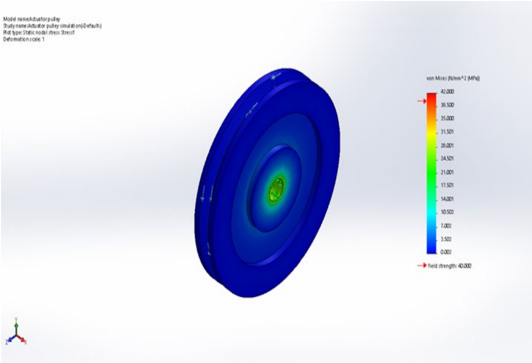

Fig 9: Stress analysis

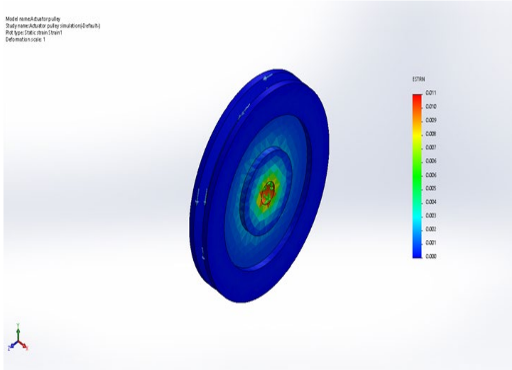

Fig 10: Strain analysis

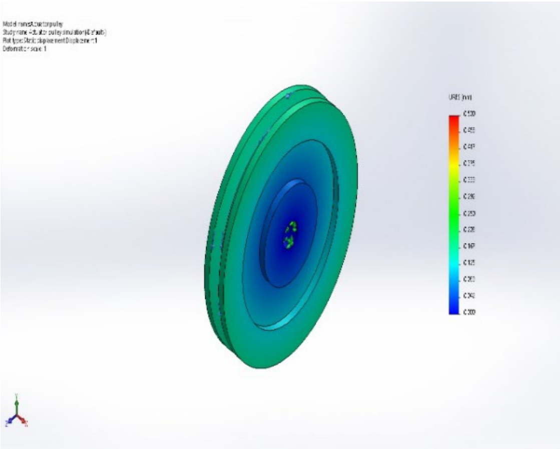

Figure 11: Deformation Plot

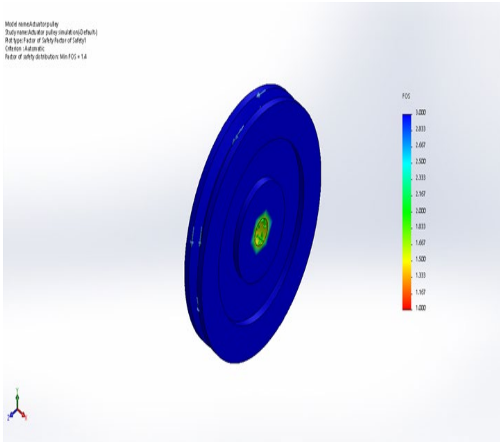

Figure 12: Factor of Safety Plot

Fig 13: CAD model of tendon

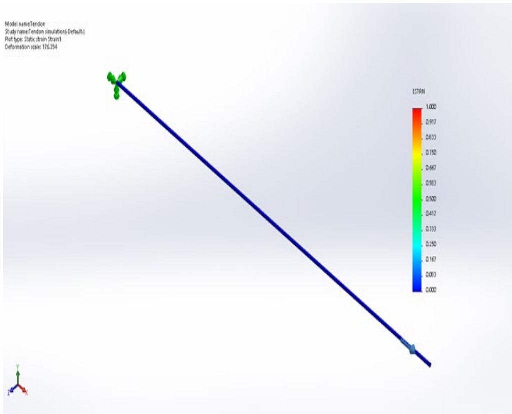

Fig 14: Strain analysis

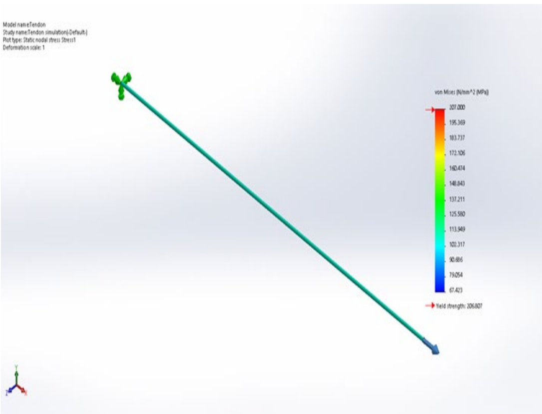

Fig 15: Stress analysis

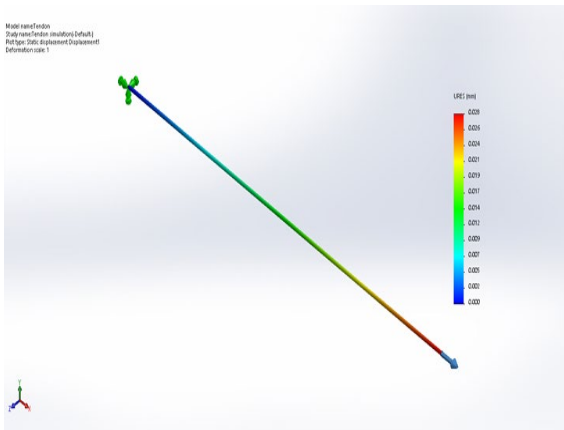

Fig 16: Deformation Plot

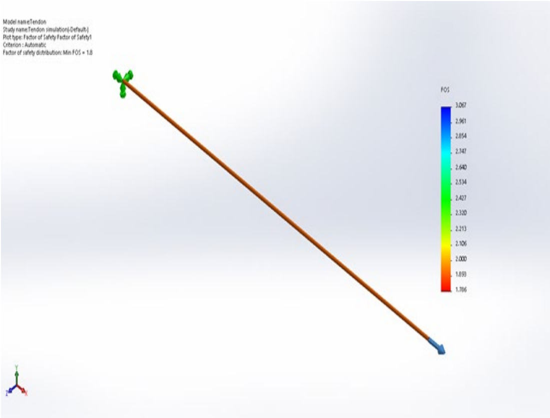

Fig 17: FOS Plot

as can be seen in figure 7. Table no 3 shows all the analysis output of the palm of the system in the prosthetic hand for function of opening and closing of the hand.

In another condition, load is applied at the pulley used in the system. The maximum amount of equivalent von-mises stress can be found in yellow colour. The figure 8 gives the value of maximum stress that is 28.925 MPa. Figures 9 and 10 represents the equivalent elastic and strain total deformation for the pulley of the system. The pulley is less deformed by the value of 0.0283 mm and maximum elastic strain is calculated was 0.000492. Figure 11 and 12 are showing the deformation plot as well as factor of safety plot. Table no 4 shows all the analysis output of the pulley of the system in the prosthetic hand for tendon to function of opening and closing of the hand.

In next case the load is applied at the tendon of the prosthetic hand which is transferring the motion to finger from motor. Figure 13 shows the CAD model for the tendon of the hand. Stress and strain analysis is shown in the figure 14 and 15. Figures 16 and 17 represents the deformation plot and factor of safety plot. Table no 5 gives all the analysis output of the tendon of the system in the prosthetic hand.

3. Conclusion

By the use of FEM safe design could be generated and the stress analysis could be achieved without the destruction of the prototype. Suitable material could be selected for the fabrication by ease of this software. Two major advantages have been concluded. Firstly, fabricating prosthetic hands with 3D printers are quite inexpensive. The increase in implementation of consumer grade 3D printers and the reductionin the charges of printer filament implies that spare and advanced parts may now be printed in numerous materials at a very cheaper price and the above mentioned design is safe to be fabricated.

Second, this technique allows for customization for large number of people, for their needs of high quality of prosthetics. By the means of this technology, everyhand can be designed and developed to meet a definite user necessity, together with the dimensions of hand as well as its intricacy. The dimensions of every hand can inexpensively be presented to match the exact size of the other hand. There are some people who lack the acceptable motor skills or want to have unconventional prosthetic hand with high number of degrees of freedom and multifunctional. All because of the flexible nature of the prosthetic hand design, the handlers can use a basic traditional hand or upgrade any particular individual parts as they grow as well as their capabilities or preferences changes with time. Majorly famous materials like acrylonitrile butadiene (ABS), polylactic acid (PLA), polythene terephalate glycol (PETG), nylon, thermoplastic polyurethane (TPU), etc are used for 3D printing process. Carbon based nanomaterials can be used as transmission system of artificial limbs to reduce cost as they are very strong. Due to high sensitivity and memory properties ionic gels and hydrogels are used as skin of prosthetics. Metallic synthetic materials and composite materials and fiber laminate composite materials are used for skeletal structure as they have high toughness and hardness [41].

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