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RESEARCH ARTICLE

Simulation of Chinese finger grip braided sleeve designs for transtibial prosthetics

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Abstract

This work focused on the development of a below knee prosthetic that designed to eliminate various discomforts that are commonly prevalent among the general population of the amputees. The major parts of the transtibial prosthesis are foot, pylon, socket and sleeve. The sleeve-socket compatibility plays an important role in determining the comfort level of an amputee. 'Chinese finger grip braided design' for the sleeve has been proposed by few researchers for better grip and improved comfort level of the amputees. But the detailed design of the braid is not analyzed so far. In this research, two different Chinese finger grip braided designs of the sleeve were proposed and their suitability for transtibial prosthesis was analyzed. The proposed designs were modelled using SOLIDWORKS software and sufficient evaluation of the same has been carried out using OPENSIM and ANSYS software.

***Keywords*:** Transtibial prosthetics, amputee, sleeve, analysis, modelling

INTRODUCTION

Amputation is often carried out as a last resort to arrest an infection or may be due to congenital defects. This research focused on the effect of lower limb amputations (LLA) on the life of amputees and aimed to provide a design which can eliminate the common problems among the amputees. Prostheses are artificial limbs that commonly used to replace the limbs that are lost or missing [1]. Esfandiari *et al.* [2] reported that amputations, especially the lower limb amputations have a profound traumatic effect on the mental health of the amputees. A reduction in their emotional pain with time is expected, but in contrast their emotional pain often remains the same. This study has also correlated the long term side effects with prolonged prosthetic use and has documented this issue. Also, people who undergo dysvascular amputation of the leg are affected more intensely than the people who undergo amputation due to trauma [3]. It has been reported that there will be a constant change in the shape of the stub with time based on various factors such as the hydrate content in the body, oedema and so on [4]. Continuous compressive action on the stub of the amputees has been expected to deliver good dynamic balance among the amputees but the downside being that, this compressive action affects the deep leg veins of the amputees, causing their ability to control their motion to deteriorate with each passing day [5]. Further, it has been identified that under dynamic conditions, the amputees generally exert more loads on the normal foot than on the artificial limb thus, causing stiffness in gait and rapid wear of the joints in the other leg by stressing it more than it is used to [6].

A study on the feasibility of the usage of exoskeleton for the amputees is discussed by Aliman *et al.* [7] and the authors cite that there is currently no universally feasible solution wherein the lower limb amputees can benefit from these exoskeletons that are commercially available. The focus of such products has been kept on military and endurance applications, thereby suggesting that a cheaper alternative for the same can be considered. Another product that is recently gaining traction is a type of prosthesis which does not require any sockets and the prosthetic is actually mounted rigidly to the bone itself through titanium screws known as the osseointegrated prosthetics. But scientific studies report that the entire gamut of problems cannot be eliminated through this type alone and the removal the socket will only cause problems in the metal-skin and the metal-bone interface and thus, increasing the chances of infection [8]. Despite the advancements in technology, there are exist problems in the form of pain among the amputees, in addition to causing discomfort and also indirect pain such as back pain, phantom limb pain and so on. Therefore, prime importance must be given to ensure the comfort of the amputees under all circumstances so that the drawbacks can be avoided [9]. Considering all the above factors, alternate Chinese finger grip braided designs for sleeves were investigated in this research. The design was simple, metabolically efficient and cost effective. But its feasibility needed further investigation.

DESIGN AND APPROACH

Initially a study was carried out on the various prosthetics available, the complexities of each available models and their long term effects on the users. The most common types are transtibial and transfemoral prosthetics that categorized as lower limb prosthetics while transradial and transhumeral prosthetics that classified as the upper limb prosthetics. In this research, the transtibial prosthetics were considered for analysis as they could cause significantly higher emotional strain and dissatisfaction level in the patients [10,11]. The following are the components of the lower limb prosthetics.

- Foot-Ankle assembly
- Pylon or Shank
- Knee Unit
- Socket and Sleeve

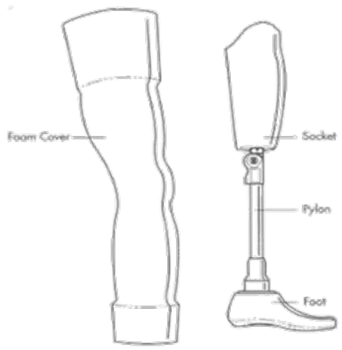


Fig. 1 Transtibial Prosthetic [12].

Foot-ankle assembly

The foot-ankle assembly provides the base of support in addition to providing shock absorption and push-off on even and uneven terrain. Four general categories of foot-ankle assemblies are non-articulated, articulated, elastic keel, and dynamic-response types.

Pylon or shank

The pylon rod or shank represents the shin of the leg and connects the assembly to the foot ankle assembly. The two major types are the endo and the exo-skeletal shank which can be differentiated by the members which provide the load supports. In the former type, a central pylon provides the vertical load support whereas in the latter type, the hard outer shell forms the supporting member.

Knee unit

Transfemoral amputations also pose an additional challenge of incorporating a prosthetic knee unit which can be considered as one of the most difficult tasks to perform, as the knee is one of a kind and exact replacement is not possible. But a degree of freedom as close as possible to the natural knee must be produced to support the weight while being able to bend and straighten, as smooth as possible. Various knee types such as single-axis, polycentric, weight-activated, manual-locking, hydraulic, and pneumatic units are available.

Socket and sleeve (suspension system)

The socket connects the residual limb and the prosthetic setup, and disperses pressure around it. A hard socket offers direct contact between the limb and the socket, resulting in decreased friction, easy cleaning and increased durability. The sole drawback is that it transmits the shocks and all the loads directly and at times damages the stub. On the other hand, a soft socket includes a liner between the socket and residual limb. This provides additional protection for the limb but may increase friction and bulk. The presence of the liner also helps in accommodating the limb in a better fashion.

The suspension subsystem absorbs shocks while walking, as the load is not a continuous-but an intermittent one that acts on the leg. The common transtibial suspensions include sleeve, supracondylar, cuff, belt/strap, thigh lacer and suction styles. Sleeves are made of neoprene, urethane or latex and used over the socket and thigh. Supracondylar and cuff suspensions are used to capture the femoral condyles and held the prosthesis on the residual limb. The belt and strap method uses a waist belt with an anterior elastic strap to suspend the prosthesis, while the thigh-lacer method uses a snug-fitting corset around the thigh. The suction method consists of a silicone sleeve with a short pin at the end. This sleeve fits over the residual limb and the pin locks into the socket. Though there are various complexities, the major problem with the prosthetic is the misalignment and improper ergonomical design of the prosthetic which can cause the majority of the problems. The socket fit, type of prosthetic suspension and alignment of the prosthesis can alter pressures on the residual limb [13-16].

MODELLING AND SIMULATION

In this research, the Chinese braided sleeves were modelled using SOLIDWORKS software. OPEMSIM, open source software developed by the Stanford University team was used for biomechanics analysis and the outcomes like hip flexion angle and Knee flexion angle were used for calculating the maximum load. Finally, ANSYS software was used for analyzing the Solidworks modelled sleeve designs and the maximum load obtained was applied during the simulation.

Chinese braided sleeve

The Chinese braided sleeve is fundamental in eliminating the various drawbacks described in the aforementioned paragraphs [17]. However the details pertaining to the number of braids, cross section of the braids, load acting on braided and unbraided sleeve are not available in the literature. The braid can be made using a material with good elasticity, while the vast combinations of the prospective materials that can be used to produce such a braid open up new research frontiers in the future.

The next step was to design the required product using any design software. SOLIDWORKS has been selected for the design of this helix as the software could provide an inbuilt feature in Helix design which facilitated in creating alternatively varying diameter helix. The basic dimensional parameters such as the height (300 mm) and outer diameter (100mm) of the sleeve were not varied. Only the number of braids was varied as shown in Figs. 2 and 3 and compared with the same dimension unbraided design in Fig 4.

Load estimation

Open source software developed by the Biomechanical engineering department of the Stanford University OPENSIM, was used for making an analysis of the various angles at which the load was transferred to the prosthetic limb.

Fig. 2 Sleeve with rectangular cross section and 10 braids in number (Design A).

Fig. 3 Sleeve with rectangular cross section and 20 braids in number (Design B).

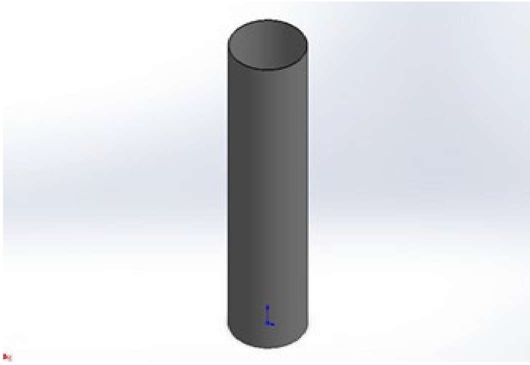


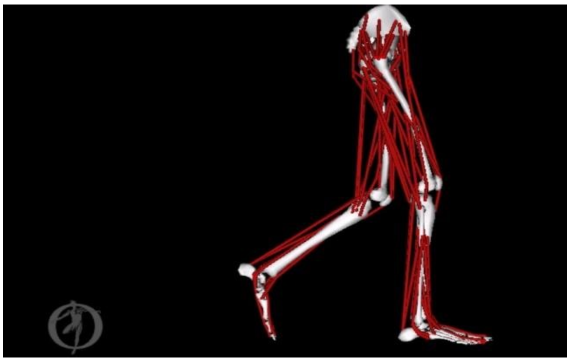
Fig. 4 Unbraided sleeve used in present designs.

A predefined biped model from the software, viz, "Separate legs with muscles" was chosen and the predefined motion, viz, "normal gait" was fed to the model as shown in Fig. 5. The software considers the variation in walk pattern from individual to individual based on factors like terrain differences. A normalized gait was simulated and hence, the possibility of errors was marginalized. Keen observation showed that during gait, the body weight tended to shift from one leg to another leg in a regular continuous pattern. At one instance, max load acted on the joints and transferred to the ground, as each leg tended to take up the entire body load. This instance was determined from the motion capture images (ref Fig 5). This maximum load condition was characterized by the point at which the hip flexion angle was minimum, thereby transmitting the entire body weight to the knee joint. This instance was referred to as the median position or the max load position (ref Fig 5(c)). Angles obtained at the joints are shown in Table 1.

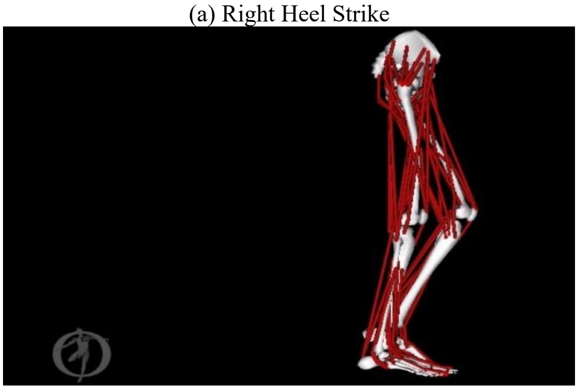
Table 1 Various angles of hip and knee during phases of bipedal motion.

Position	Hip Flex Angle (deg)	Knee Flex Angle (deg)
Right heel strike	24.7	4.147
Left foot rise	20.24	17.037
Maximum load position	0.33	6.594
Left heel strike	10.825	5.839
Right foot rise	7.142	39.60

(a) Right Heel Strike

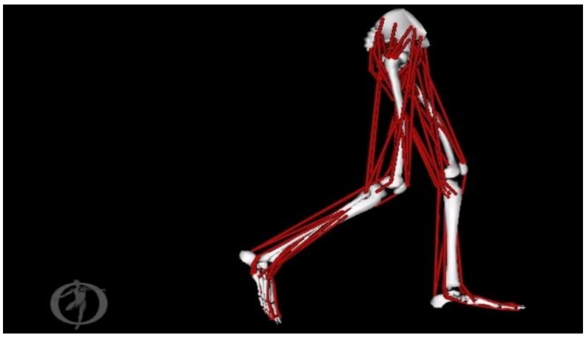


(b) Left Foot Rise



(c) Maximum Load Position

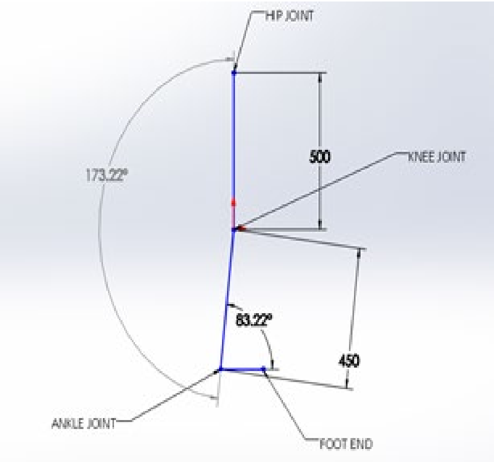
(d) Left Heel Strike.



(e) Right Foot Rise

Fig. 5 Normal gait modelled using OPENSIM.

The angle estimation obtained from the maximum load position was used for calculating the load acting on the sleeve through a free body diagram. The approximate body weight distribution among the body segments for an average individual was finalized from the historical data [18]. A sample case was considered by assuming the body weight as 68 kg and the body segment weights were calculated for the above case. It was estimated that, approximately upper and lower trunks were equal to 68.02% of body weight and thigh was equal to 9.88% of body weight. The artificial foot alone weighed between 0.5 kg and 2 kg [19]. Hence, upper and lower trunks constituted to 46.25 kg (462.54 N), thigh constituted to 6.72kg (67.2 N) and prosthetic limb constituted to 2 kg (20 N). The free body diagram of the limb is represented in Fig 6 (a) and (b).



Length in mm and angle in degrees

Fig. 6 (a) Free body diagram - Representation of angle

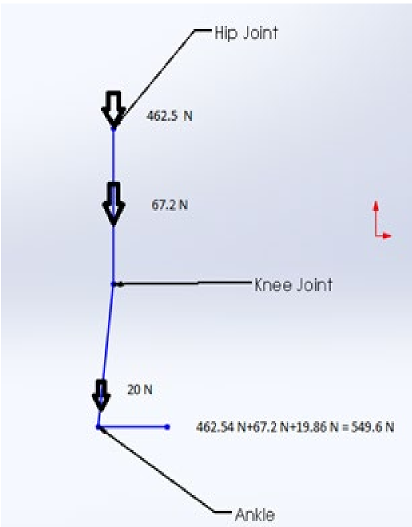


Fig. 6 (b) Free body diagram - Representation of loads.

From the free body diagram, the total load acting on the sleeve was estimated as 550N. This sample load was applied to the sleeve by importing the sleeve designs (both braided and unbraided) to ANSYS software. Few researchers have performed finite element analysis on biomedical applications [5, 20-21]. In this paper, the sleeve material was chosen as silicon rubber and the properties of the same are given in Table 2.

Table 2 Properties of silicon rubber.

Parameter	Value
Elastic modulus	**5 x 10^7 N/m^2**
Shear modulus	**2 x 10^7 N/m^2**
Poisson's Ratio	**0.49**
Mass Density	**2300 kg/m^3**
Tensile strength	**5.5 x 10^6 N/m^2**
Thermal conductivity	**2.55 W/mK**
Specific heat	**1300 J/Kg K**

RESULTS AND DISCUSSION

The Chinese braided sleeve designs with rectangular cross section and ten braids have been designated as 'A' and the one with twenty braids has been designated as 'B'. The sample load calculated using the free body diagram was applied on the sleeve designs and the final analysis was performed using ANSYS software.

Figures 7 - 8 indicate the analysis performed on unbraided design, braided design 'A' and braided design 'B', respectively, and the results of the analyses performed mentioned in Table 3. The finite element modelling was done based on the following assumptions: 3D mesh; isotropic with element length 0.01 m; bottom region fixed and top region loaded with a maximum load of 550N.

Table 3 Finite element simulation results.

Output	Present Design	Braided Design – A	Braided Design – B
Directional Deformation (radial direction) (m)	1.4 x 10^{-7}	**0.034**	**0.22**
Directional Deformation (longitudinal direction) (m)	2.9 x 10^{-6}	**0.019**	**0.14**
Maximum Principal Stress (N/m^2)	2.7 x 10^6	**5.3 x 10^8**	**1.3 x 10^9**
Shear Stress (N/m^2)	3.1 x 10^5	**4.6 x 10^8**	**7.2 x 10^8**

It can be observed from Fig. 7 to 9 that the maximum principal stress and the shear stress values in the unbraided design were less than both the Chinese braided designs. Moreover, the values of the principal stresses were more than the tensile strength of the material, in the case of Chinese braided designs. A careful observation of the finite element analysis outcome indicated that the stresses are maximum only at certain points. Though this condition is not favoured, it is expected due to the nature of the design. This scenario can be overcome by 'sandwiching' the Chinese braided design between a silicone layer and the flexible socket.

Considering the directional deformation, radial direction deformations have to be higher than longitudinal direction. Deformation in the radial direction in turn corresponds to the grip around the stump region. Higher the value, greater will be the grip around the stump. Compared to the unbraided design, directional deformation in radial direction is greater in the Chinese braided designs. Also, when the number of braids is increased, the deformation tends to increase. Hence, the finer the braid, the more the deformation in radial direction which in turn means greater grip around the stump. Thus, Chinese braided design – B provided better grip than the other two designs. The deformation values were higher than usual because there was no stump region modelled and included in the ANSYS window. With the stump region, deformation automatically can be restricted.

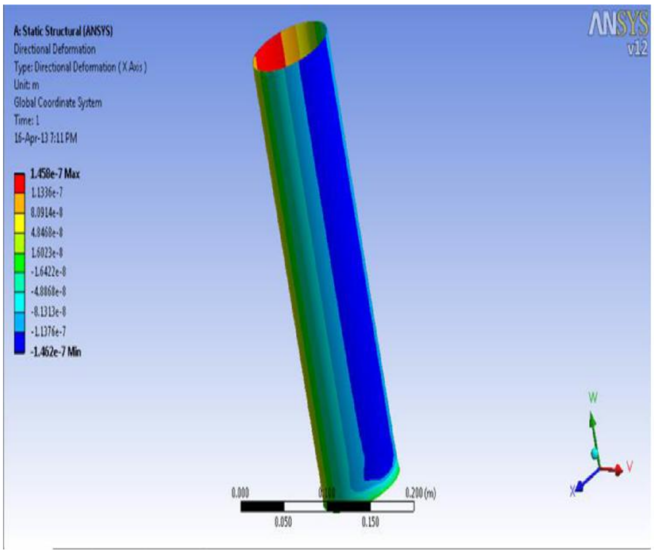


Fig. 7 (a) Directional deformation (radial direction)

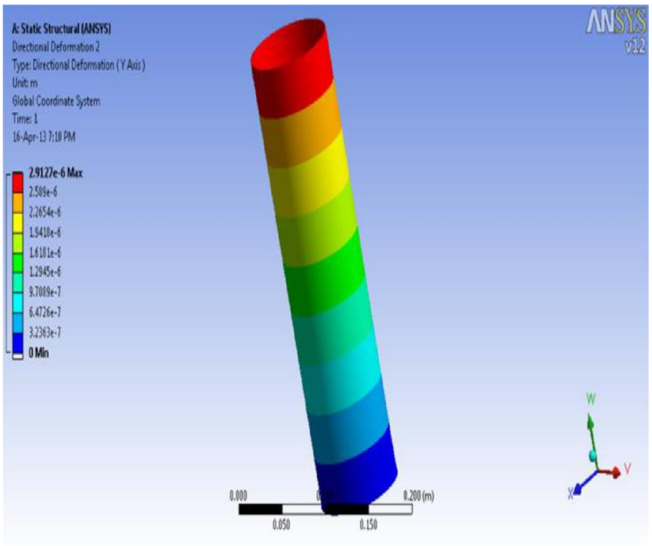


Fig 7. (b) Directional deformation (longitudinal direction)

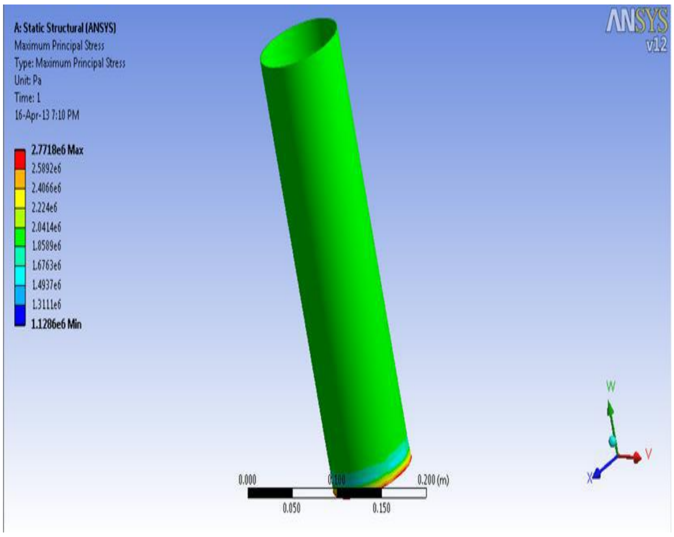


Fig. 7 (c) Maximum principal stress

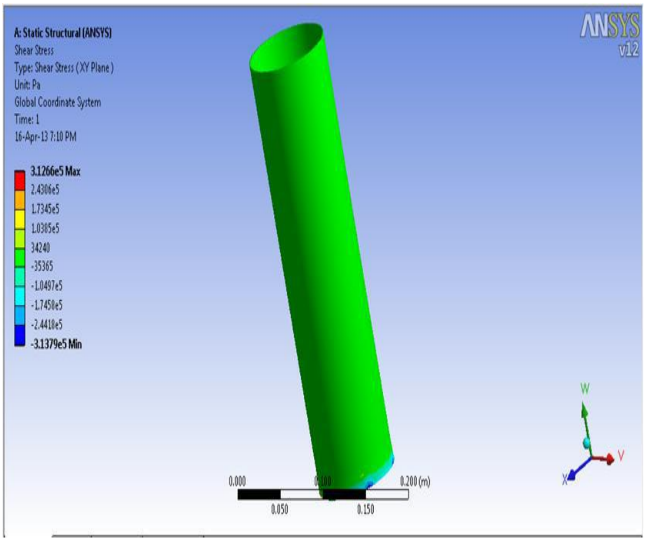


Fig. 7(d) Shear stress

Fig. 7 Analysis of unbraided design.

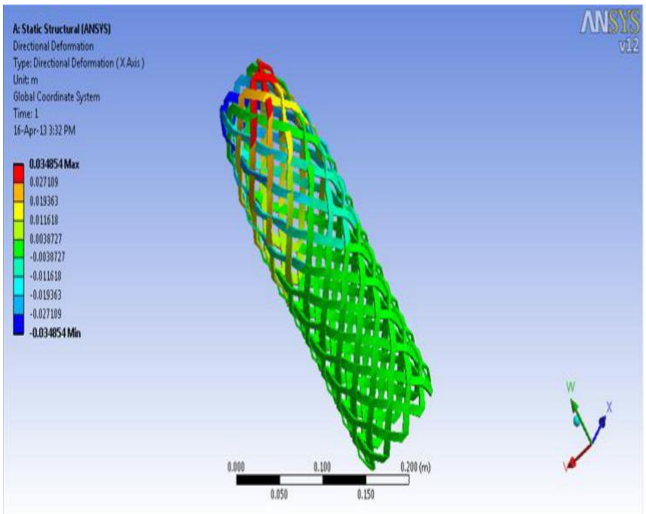


Fig. 8 (a) Directional deformation (radial direction).

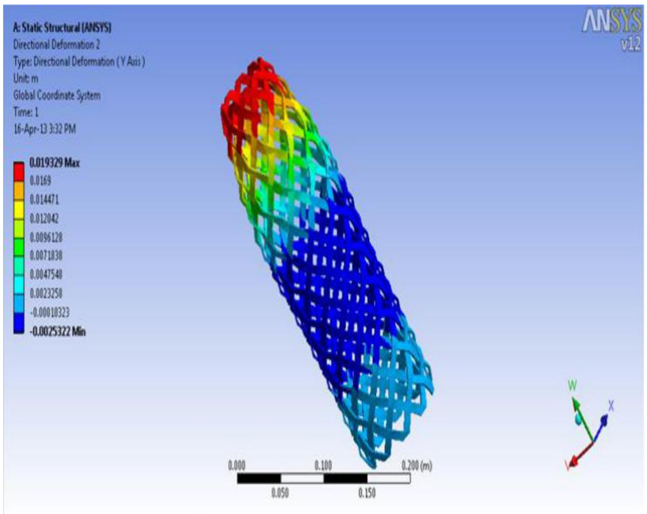


Fig. 8 (b) Directional deformation (longitudinal direction).

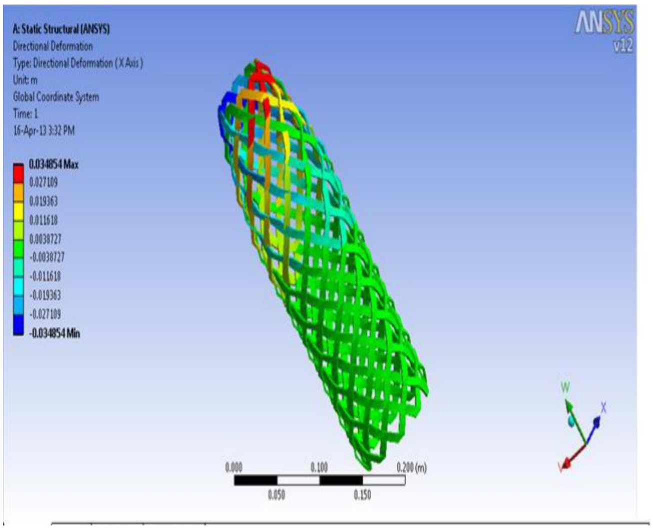


Fig. 8 (c) Maximum principal stress.

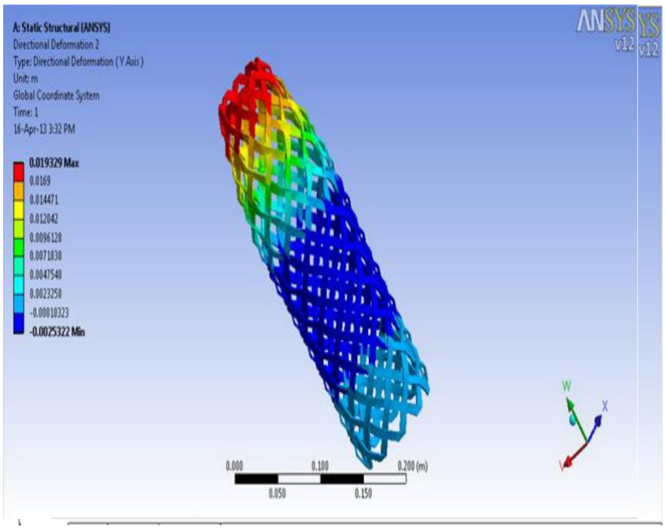


Fig. 8(d) Shear stress.

Fig. 8 Analysis of braided design – A.

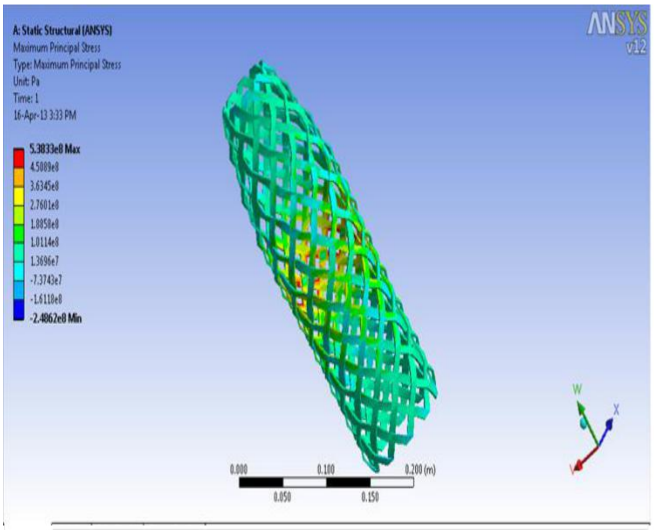


Fig. 9 (a) Directional deformation (radial direction).

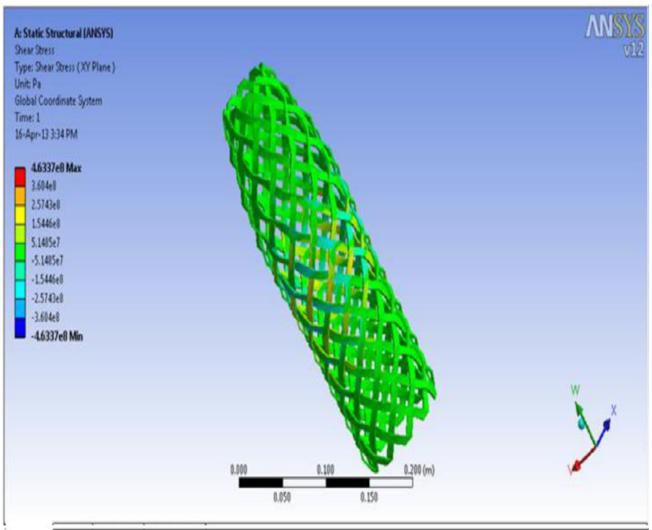


Fig. 9 (b) Directional deformation (longitudinal direction).

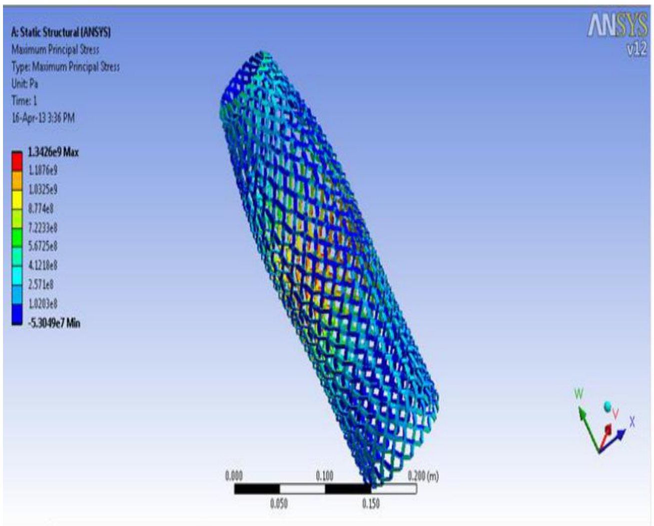


Fig. 9 (c) Maximum principal stress.

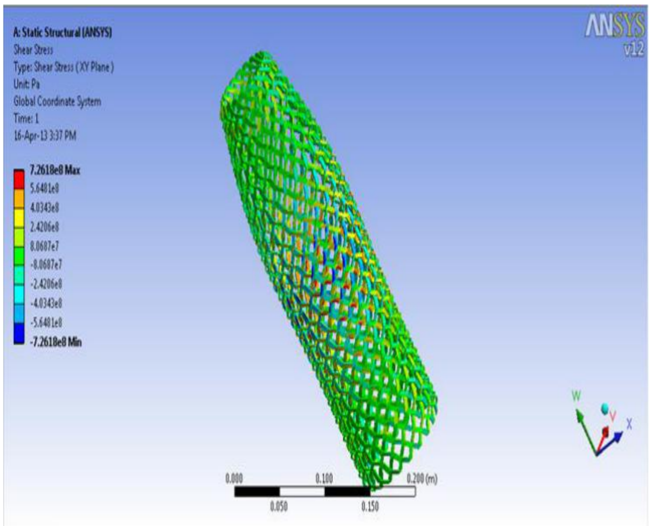


Fig. 9(d) Shear stress.

Fig. 9 Analysis of braided design – B.

CONCLUSION

In this research work, two Chinese finger grip braided sleeves, proposed for transtibial prosthetics, were modelled and analyzed to infer their suitability for practical applications. The existing sleeve design was also simulated for the same sample load and the outcomes were compared with braided designs. Following conclusion should be drawn from the analysis.

- The maximum principal stress and the shear stress in the existing unbraided design were less when compared to the braided sleeves. This was an expected result as the quantum of material in braided sleeve was less when compared to the unbraided sleeve.
- Sandwiching the Chinese braided sleeve between a silicone layer and the flexible socket might solve the problem. Lycra laced silicone material sandwiched between elastic members may be simulated in future researches.
- As the number of braids was increased, the radial deformation around the stump region was also increased and hence, the grip was improved. Therefore, Chinese braid – B was superior to the other two designs in this aspect.

In general, the comfort level of the amputees was improved while using the Chinese finger grip braided design but the safety aspect of the design needed to be addressed. Hence, the Chinese finger grip braided design is suitable for sleeves only after due modifications.

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