Development of 3D printed orthotic device for flat foot problem

Article *in* Materials Today Proceedings · February 2021

DOI: 10.1016/j.matpr.2020.12.487

2 authors, including:

Shivraj Narayan Yeole
VNR Vignana Jyothi Institute of Engineering & Technology

11TH INTERNATIONAL CONFERENCE ON MATERIALS PROCESSING AND CHARACTERIZATION

Development of 3D Printed Orthotic Device for Flat Foot Problem

(Manuscript ID: MATPR-D-20-11482)

S. Koteswari and Dr. Y. Shivraj Narayan
Department of Mechanical Engineering

TAMASOMA JYOTIRGAMAYA
Estd. 1995

VNR Vignana Jyothi Institute of Engineering & Technology
Pragathi Nagar, Nizampet (S.O), Hyderabad 500090

Outline of Presentation

- **Abstract**
- **Introduction to Foot Insoles**
- **Design Process of Foot Insole**
  - Data Acquisition and Image Processing
  - Measurement of Calcaneal Pitch Angle and Subtalar Joint Angle
  - Design of Foot Insole
- **Analysis and Optimization of Foot Insole**
  - Calculating Weight of the Body from Foot Length
  - Analysis on Designed and Modified Insole
  - Lattice Structure Optimization
  - Analysis of lattice patterns
  - Generating Internal IWP Pattern Insole
- **Results & Conclusion**
- **References**

Abstract

Foot pain, mainly flat foot, has been a major health issue of people all over the globe. It has been attributed to their sedentary lifestyle as compared to the past. Prime reasons for foot pain to occur even among normally arched individual are zero exercise, putting on excessive weight, prolonged sitting and standing etc. People in the age group of 60 to 65 years face the effect of flat foot. It is observed that even people from the middle age group of 40 to 60 years are also developing this issue because of their lifestyle. People from the age groups lesser than these are also developing flat foot issues in the recent times. Doctors have suggested treatments like performing physical activities, consuming medicines and using orthotic aids to control the problem. Orthotic aids commonly suggested are insoles, cushions, massage pads, medical shoes etc. Utilization of orthotic aids provides relaxation to the foot. Silicon material is typically used for making orthotic aids through injection molding process. However, it is also reported that there is lack of comfort while using these devices. To resolve this issue, an attempt is made to provide an alternative to the traditionally manufactured orthotic aids. Prime focus has been on designing and developing a 3D printed orthotic aid that improves lower limb alignment of foot and also promotes relief to the various foot pain issues. This comprises achieving an optimized design through analysis and manufacturing using 3D printing.

Keywords: Flat Feet; 3D Printing; Orthotic Devices; Fallen Arch

Introduction

Custom made foot insoles are developed to overcome different pathologies.

Insoles are preferred for people suffering from[1].

- Pronation
- Supination
- Plantar Fasciitis
- Arch Pain
- Archilis Tendon
- Motion Neuroma
- Hallux Rigidus
- Hallux Limitus
- Arthritis
- Morton's Toe
- Diabetes
- Heel Spurs
- Heel Pain
- Shin Splints
- Metatarsalgia
- Obesity
- Over Standing
- Athletics And Sports

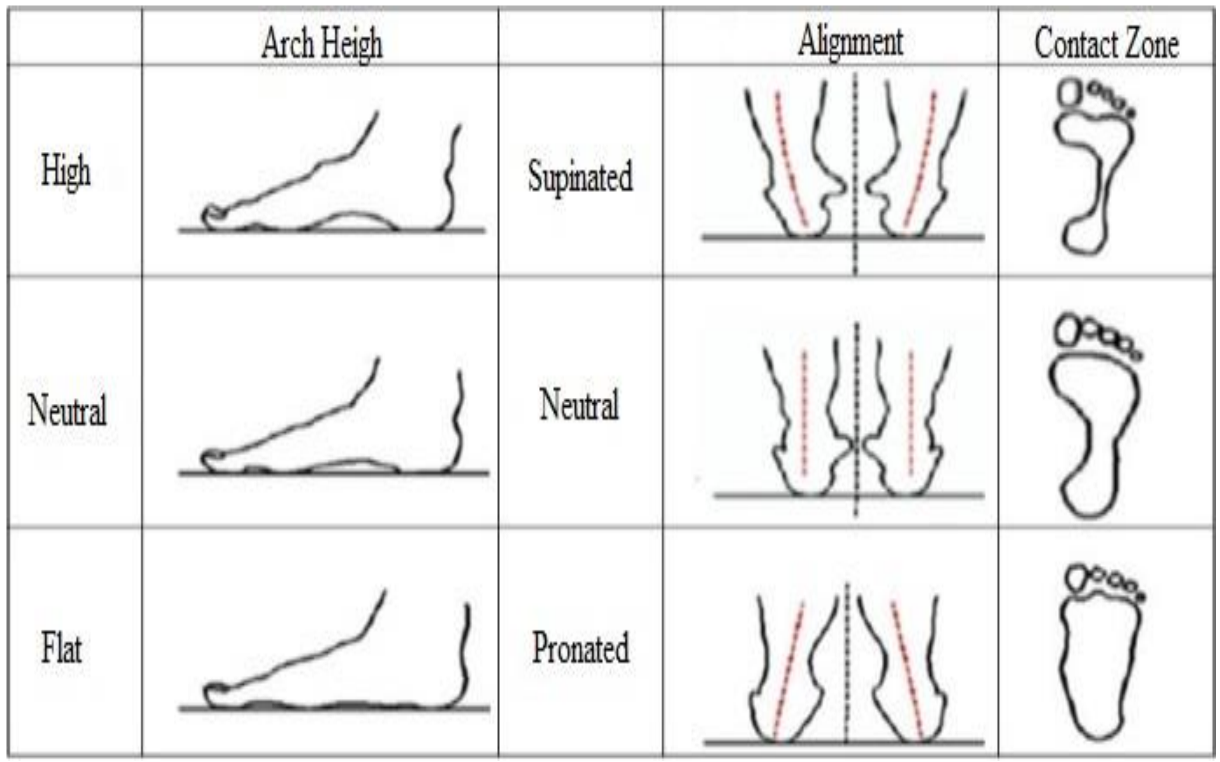

Fig. 2. Types of Foot Arch

Data Conversion

Data Conversion

- 3D slicer software is used initially to convert MRI scans of DICOM data for image processing.
- DICOM Data is converted to STL format . STL file is imported to mesh mixer where loss of skin data on external face of foot is detected.

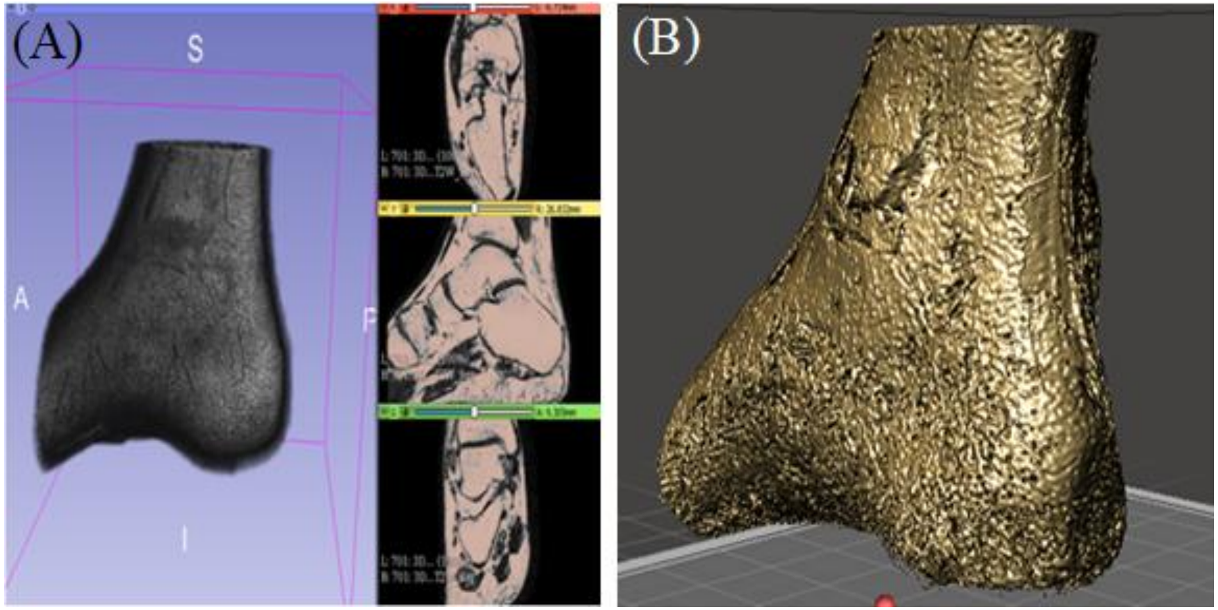

Fig. 1. (A) DICOM Data of Skin; (B) STL File of Foot

Data Acquisition and Image Processing

- DICOM data of two patients were acquired with different age groups 18 and 74 years suffering with mild joint effusion at tibiotalar, subtalar and talonavicular joint foot injuries.
- Invesalius software is used for image processing , 150 and 192 2D slices were identified for both cases.
- segmentation process is done with threshold values of skin tissues as -718 and bone as 226[3].

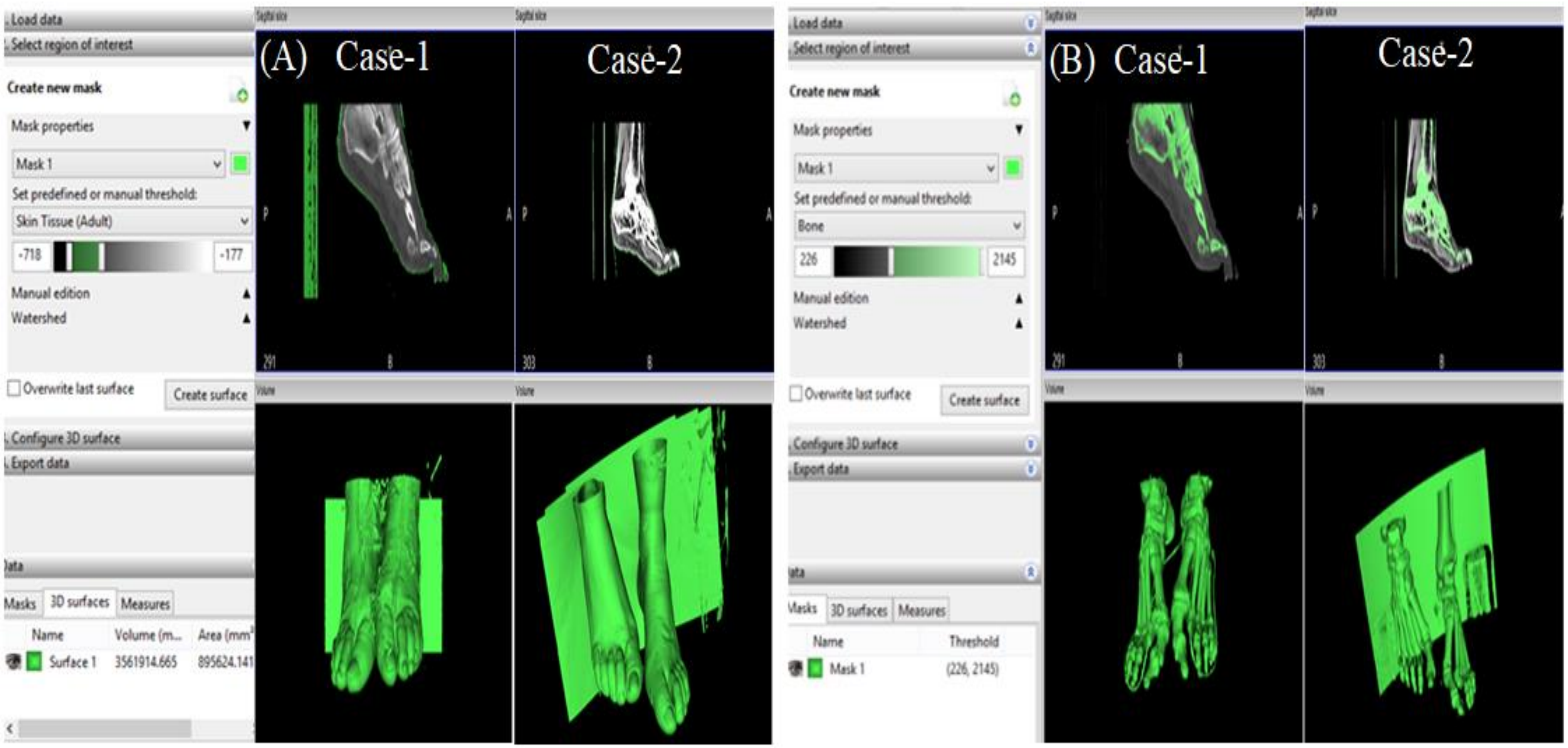

Fig. 2. (a) Threshold data of skin; (b) threshold data of bone

Flat Foot Identification

Flat foot condition can be identified with calcaneal pitch and subtalar joint angles.

- **Calcaneal Pitch Angle**: The angle from navicular tuberosity connecting calcaneus inferior point to metatarsal for case-1 is 26.17° and case-2 is 17.25°. This indicates flat foot condition for case-2[4].

- **Subtalar Joint Angle**: Only case-2 is performed with this evaluation to confirm flat foot condition. From the calcaneus inferior base to the central Axis of tibia the angle is 74° this indicates flat foot[5].

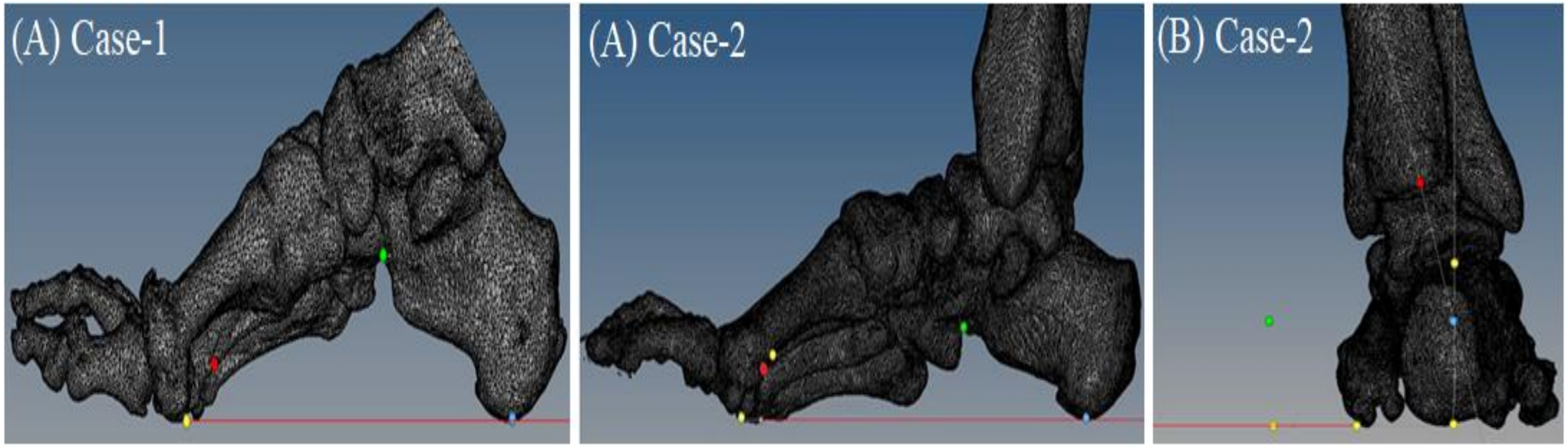

Fig. 3. (A) Calcaneal Pitch Angle for Case1 and 2. (B) Subtalar Joint Angle for case 2.

Design of Foot Insole

- Foot is one of the complex structure in human anatomy. Foot length is recognized as 244.47 mm from reverse engineering represents insole size as 7 according to English system[6].
- CATIA software is used to design foot insole for case II by considering multi curve sections of foot in developing top face of insole. The front face is designed according to rocker curve structure, stiffener at arch and minimal curve at rear end.

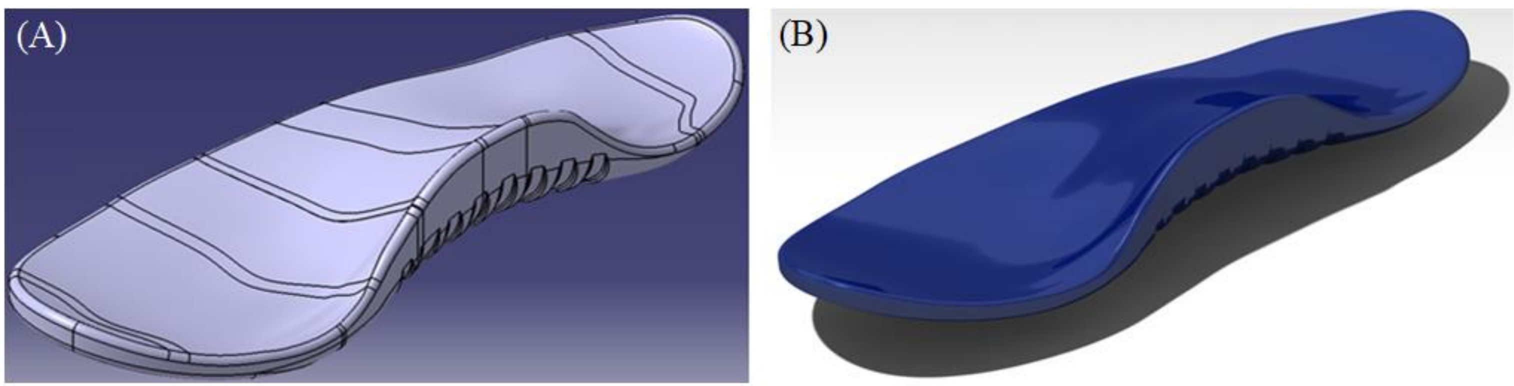

Fig. 4. (A) Design of Foot Insole; (B) Render Image of Foot Insole.

Calculating Weight of the Body from Foot Length.

Calculation of body height from foot length:
Worldwide Regression formula for evaluating female right foot height;
Height = Value of constant + Regression coefficient x Foot length (7)
Value of constant is 89.82 and regression coefficient is 2.95. On calculating, the body height is 161.9cm.

Estimation of body weight from height of a person:
According to National institute of health standards for 64 inch height estimated weight of normal person is 110 to 140 lbs, over weight is 145 to 169 lbs, obesity is 174 to 227 and over obesity is 232 to 314 lbs.

Considering over obesity condition, height with weight parameters BMI is calculated.
BMI = Weight (kg) / Height^2 (meters) = 142.428 / 1.62 = 54.3 (8)
This indicates over obesity. Further analysis is done considering maximum weight on designed and modified insole for safe conditions.

Material properties of insole:
Static structural analysis is performed in ANSYS software during stance phase on insole with different materials.

Table 1. Material Properties of Ninja Flex, Flex PLA and PLA[9].

S.No.	Material	Young's Modulus (MPa)	Poisson's ratio	Density (Tonn/mm^3)
1.	Ninja Flex	150	0.34	1.04e-9
2.	Flex PLA	1487.9	0.342	1.05e-9
3.	PLA	3500	0.33	1.24e-9

Analysis and Optimization of Foot Insole

Analysis on Designed and Modified Insole:

Loads and boundary conditions are assigned with all Degrees of freedom on contact faces of insole with shoe and considering over obesity 1396.71 N pressure on top face of insole.

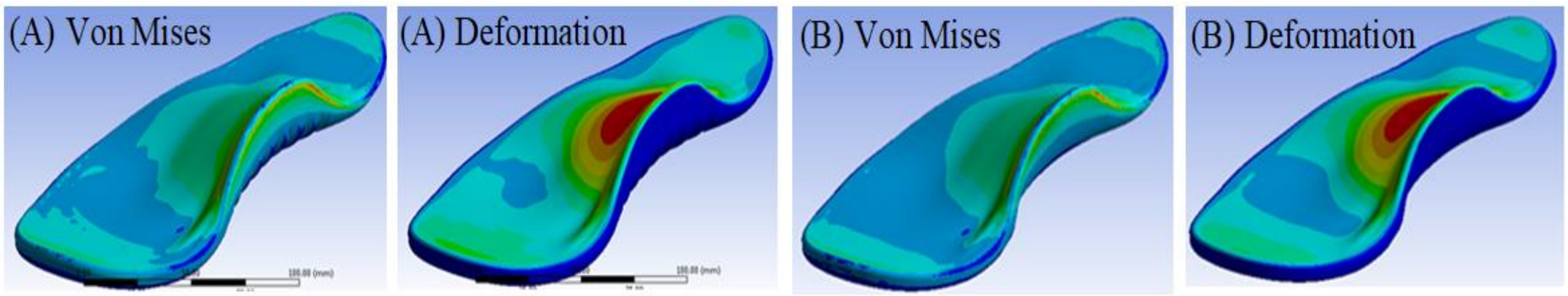

Fig. 5. (A) Analysis Results of Designed Insole; (B) Analysis Results of Modified Insole.

Analysis results for designed and modified insole with ninja flex, flex PLA, PLA materials for over obesity condition is listed below.

Table 2. Analysis results of insole with designed and modified insole.

S.No.	Analysis Results	Insoles	Ninja Flex	Flex PLA	PLA
1.	Von Mises	Designed	0.18914	0.18847	0.19246
		Modified	0.20417	0.20339	0.20801
2.	Deformation	Designed	0.010462	0.0010517	0.00045469
		Modified	0.010398	0.0010451	0.00045204

Analysis on Modified Insole

Contact analysis is performed on modified insole with dorsiflexion angle 20°[10], plantar flexion with angle 30°[11], cylinder support at mid foot, cylinder supported at fore foot and hind foot with Ninja flex material considering over obesity condition. Loads are applied at heel, metatarsals and all degrees of freedom on bottom face.

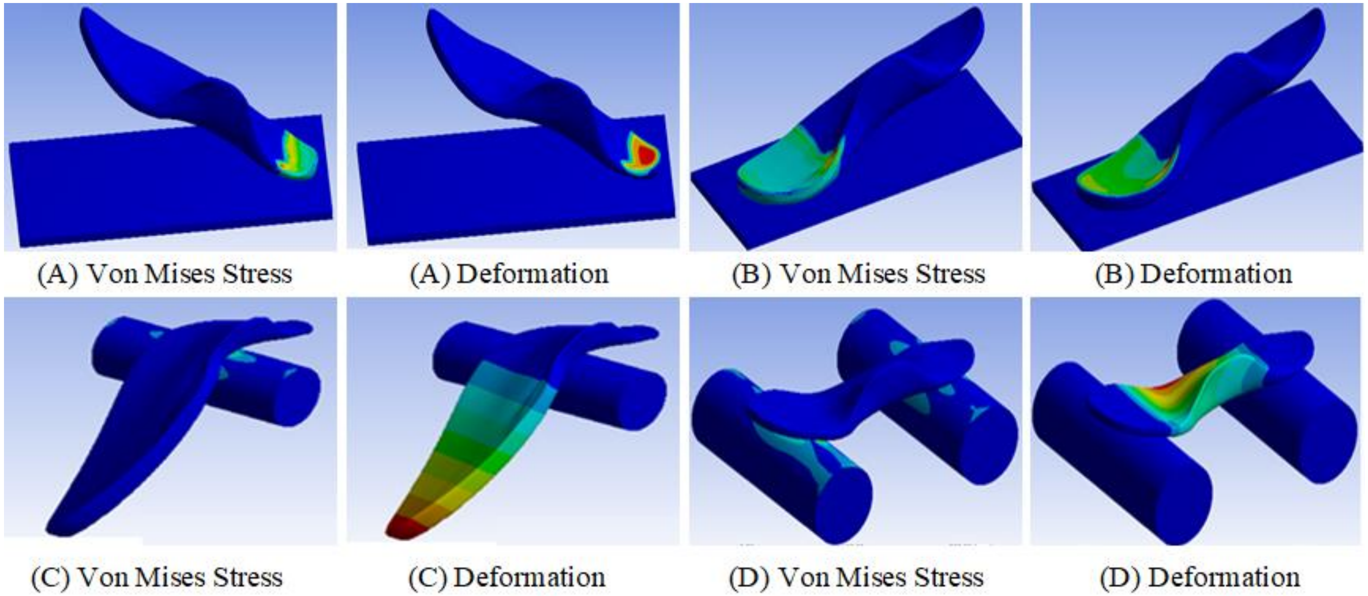

Fig. 6. Analysis Results of Insole (A) Dorsiflexion; (B) Plantar flexion; (C) Cylinder Support at Mid Foot; (D) Cylinder supported at fore foot and hind foot.

Analysis Results on Modified Insole

- Insole with ninja flex material results represents that at plantar flexion the deformation is more than dorsiflexion. Similarly load acting at mid foot has more deformation than at hind and rare foot condition. This shows similar effect even on flex PLA and PLA materials.

Table 3. Analysis results of insole Gait cycle and with cylinder supports.

S. No.	Material	Contact Analysis Results	Start and end Gait cycle		With cylinder supports	
			Dorsiflexion	Plantar Flexion	At mid foot	At hind and rare foot
1.	Ninja Flex	Von Mises	0.26176	0.40548	955.6	326.1
		Deformation	0.0090138	0.017499	212.98	21.479
2.	Flex PLA	Von Mises	0.26135	0.40493	857.12	238.22
		Deformation	0.00090266	0.0017601	32.261	1.6602
3.	PLA	Von Mises	0.2629	0.40822	797.28	269.6
		Deformation	0.00039878	0.00075819	18.956	3.0826

Lattice Structure Optimization on Modified Insole

- BCC, OCTO, IWP lattice structures are modelled in 32x32x16 mm space using CATIA software[12-15].
- BCC lattice linear cellular structure, struts are modelled with diameter 0.8mm in 4mm cuboid space (A), BCC lattice curved struts are developed with similar parameters(B), BCC lattice curved struts are developed by placing 0.4 mm plates at 4mm spacing (C), BCC lattice curved struts are developed by placing 0.4 mm plates at 2mm spacing (D).
- OCTO surface based unit cell is modelled with hollow sphere at face centred (E), OCTO surface based unit cell is modelled with hollow sphere at face centred with collar centre pocket (F), OCTO surface based unit cell is modified with square and elongated hole at zero stress effecting zone (G).
- Hexagon unit cell is developed with in-circle diameter 4mm and developed as pattern (H).
- Secondary IWP lattice structures originated from BCC surfaces has higher compression strength (I).

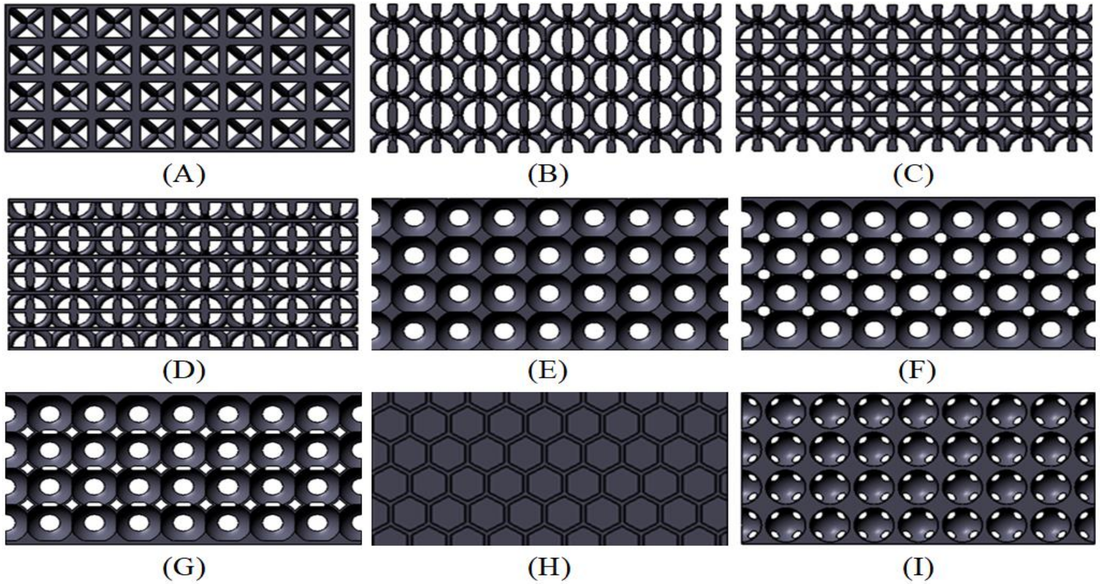

Fig. 7. Modelling of BCC, OCTO, IWP Lattice Structures

Analysis of Lattice Patterns

- Static structural analysis is performed on lattice patterns in Hypermesh software using OptiStruct solver.
- Pre-processing includes geometry clean up, meshing, quality of mesh, add material properties, loads and boundary conditions.
- Tetra mesh is generated with proximity, curvature, feature angle 300, minimum element size as 0.05 and element size as 0.2 mm [16].
- Quality of mesh is verified with warpage, skew, aspect ratio, chordal deviation, tet collapse, volume skew etc.
- Loads and boundary conditions are applied with pressure from top face and all degrees of freedom on bottom face.

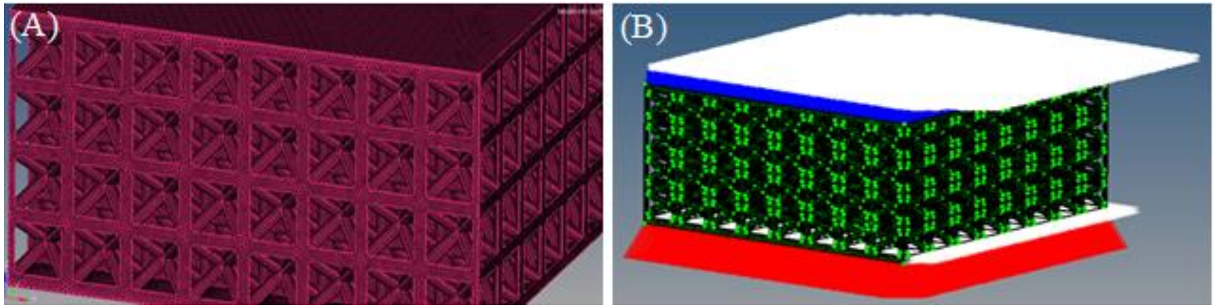

Fig.8. (A) 3D Tetra Mesh ,Quality Parameters; (B) Loads and Boundary Conditions.

Analysis Results of Lattice Patterns

Post processing results, Deformation and Von Mises stresses of patterns are visualized in Hyperview software.

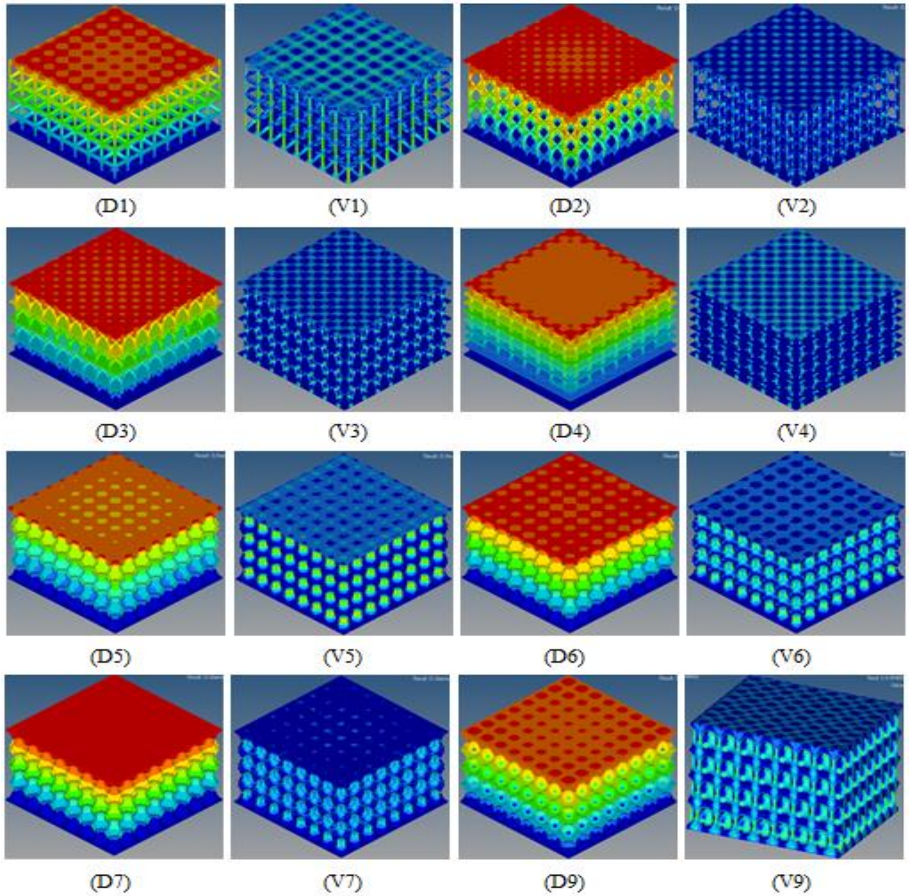

Fig. 9. (V1-V9) Von Mises Stress of patterns (A-I), (D1-D9) Deformations of patterns (A-I).

Analysis Results of Lattice Patterns

In all the patterns region of stress is concentrated at every unit cell except for IWP pattern where the maximum stress is concentrated at the last layer of unit cell this indicates high compression strength of IWP pattern. Depending on this criteria and results obtained above IWP pattern is chosen as infill for insole.

Table 4. Analysis results of Lattice Patterns

S.No.	Lattice pattern	Volume (mm^3)	Reduced volume (%)	Von-Mises Stress (MPa)	Deformation (mm)
1.	BCC linear struts	597.402	61.171	2.764	3.537e-03
2.	BCC curved struts pattern 1	392.475	74.448	4.851	3.559e-03
3.	BCC curved struts pattern 2	535.702	65.123	3.687	3.118e-03
4.	BCC curved struts pattern 3	694.106	45.189	2.806	2.783e-03
5.	OCTO pattern 1	799.77	47.931	1.268	1.234e-03
6.	OCTO pattern 2	666.349	56.617	1.873	1.582e-03
7.	OCTO pattern 3	635.741	58.160	2.852	1.945e-03
8.	Hexagon	536.353	65.081	2.621	1.457e-03
9.	IWP	633.077	58.784	2.173	1.862e-03

Generating Internal IWP Pattern Insole

- IWP Sheet based cellular material exhibits attractive mechanical properties such as stiffness and strength.
- Along the total path of insole IWP patterns are embedded and partitioned with enclosed surface of insole.
- Further the external layer of insole is added with 1mm thickness and merged with internal IWP patterns.
- Optimized results with respect to weight for designed, modified and IWP pattern insole is as shown in Table 5.

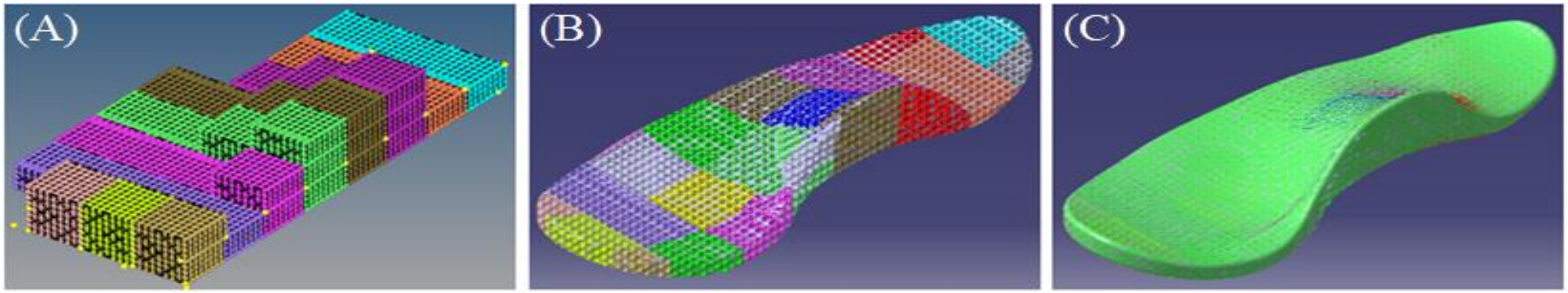

Fig. 10. Process of developing IWP pattern Insole (A) IWP pattern arranged on insole; (B) Split operation; (C) Final IWP patterned insole.

Table 5. Optimized results of Designed, Modified and IWP pattern insole

S.No.	Material	Weight of designed insole (g)	Weight of modified insole (g)	Weight of IWP lattice insole (g)
1.	Ninja Flex	196.7338	181.829	74.9
2.	Flex PLA	198.625	183.578	75.66
3.	PLA	234.567	216.797	83.09

Conclusions

- Flat foot is one of the major cause for several foot problems and lower limb alignment. Neglecting this would affect body parts particularly along sagittal plane.
- Pes planus occurs when plantar fascia ligament falls down from normal position. To overcome this problem, patient specific insole is designed and optimized for improving alignment of body and providing better comfort even during regular usage.
- Initial design is developed through reverse engineering, further modified and optimized with lattice pattern in enclosed insole.
- Finite element analysis is performed on both stages of design optimization process with 3D printing materials.
- Ninja flex material insole weight is deducted to 61.93%, Flex PLA is deducted to 61.9% which is very nearer to optimized results of Ninja Flex material.
- But Ninja Flex material is chosen due its properties which includes high abrasion resistance, shock absorbing capabilities compared to Flex PLA.

REFERENCES

1. Ma, Z., Lin, J., Xu, X., Ma, Z., Tang, L., Sun, C., Li, D., Liu, C., Zhong, Y. and Wang, L.: Design and 3D printing of adjustable modulus porous structures for customized diabetic foot insoles. Int. J. Lightweight Mater. Manuf. *2*.1, pp.57-63 (2019).
2. Koteswari S., Shivraj Narayan Y. (2021) A State-of-the-Art Review on 3D Printed Orthotic Devices for Flat Feet Condition. In: Gascoin N., Balasubramanian E. (eds) Innovative Design, Analysis and Development Practices in Aerospace and Automotive Engineering. Lecture Notes in Mechanical Engineering. Springer, Singapore. https://doi.org/10.1007/978-981-15-6619-6_29
3. Chougule, V.N., Mulay, A.V. and Ahuja, B.B.: Clinical Case Study: Spine Modeling for Minimum Invasive Spine Surgeries (MISS) using Rapid Prototyping. *Int. COPEN 226*, pp.3071-3077.
4. Mansfield, P. J., Neumann, D. A.: Structure and Function of the Ankle and Foot. J. Ess. Kins. Phys. Asst. 3, pp.311-350 (2016).
5. Norris, C. M.: Lower Limb Motion During Walking, Running and Jumping. Managing Sports Injuries, 133–142 (2011)
6. https://timesofindia.indiatimes.com/What-is-the-measuring-unit-for-footwear/articleshow/416176.cms
7. Sunitha, J., Ananthalakshmi, R., Jeeva, J.S., Jeddy, N. and Shanmugam, D.: Prediction of anthropometric measurements from tooth length–A Dravidian study. JFOS. *33*.2, pp.18-26 (2015)
8. Liu, J., Zeng, X., Hong, H.G., Li, Y. and Fu, P.: The association between body mass index and mortality among Asian peritoneal dialysis patients: J. PloS one,12.2, pp.341-347 (2017)
9. Yarwindran, M., Sa'aban, N.A., Ibrahim, M. and Periyasamy, R.: Thermoplastic elastomer infill pattern impact on mechanical properties 3D printed customized orthotic insole. J. Eng. Appl. Sci. *11*.10, pp.6519-6524. (2016).
10. Brockett, C.L. and Chapman, G.J.: Biomechanics of the ankle. J.Orthop. Trauma, *30*.3, pp.232-238 (2016).
11. Beaumatin, N., Hauraix, H., Nordez, A., Hager, R., Rabita, G., Guilhem, G. and Dorel, S.: Maximal shortening velocity during plantar flexion: Effects of pre-activity and initial stretching state. Scand. J. Med. Sci. Sports *28*.4, pp.1361-1370 (2018).
12. Maconachie, T., Leary, M., Lozanovski, B., Zhang, X., Qian, M., Faruque, O. and Brandt, M.: SLM lattice structures: Properties, performance, applications and challenges. J. *Mater. Design 183*, pp.187-194 (2019)..
13. Maskery, I., Aremu, A.O., Parry, L., Wildman, R.D., Tuck, C.J. and Ashcroft, I.A.: Effective design and simulation of surface-based lattice structures featuring volume fraction and cell type grading. J. *Mater. Design*, *155*, pp.220-232 (2018).
14. Zhao, M., Liu, F., Fu, G., Zhang, D.Z., Zhang, T. and Zhou, H.: Improved mechanical properties and energy absorption of BCC lattice structures with triply periodic minimal surfaces fabricated by SLM. J. *Mater. 11*.12, pp.2411-2416 (2018).
15. Al-Ketan, O. and Rowshan, R.: The effect of architecture on the mechanical properties of cellular structures based on the IWP minimal surface. J. Mater. Res., *33*.3, pp.343-359 (2018).
16. Dutt, A.: Effect of mesh size on finite element analysis of beam. *Int. J. Mech. Eng. 2*.12, pp.8-10 (2015).