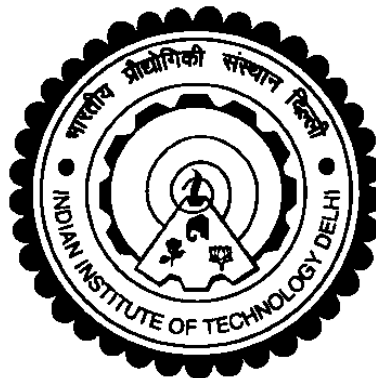


**DESIGN AND DEVELOPMENT OF HEEL PAD BY USING 3D
PRINTED BIO-INSPIRED LATTICE STRUCTURE FOR REDUCTION
OF PLANTAR PRESSURE**

PATEL BRIJESHKUMAR HASMUKHBHAI



DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

JANUARY 2025

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by

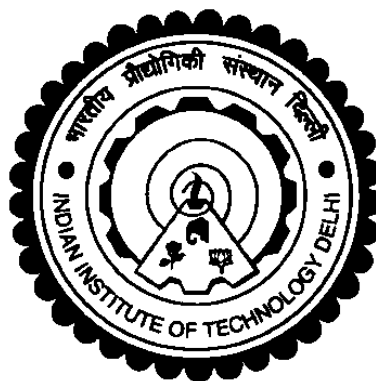
PATEL BRIJESHKUMAR HASMUKHBHAI

DEPARTMENT OF MECHANICAL ENGINEERING

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

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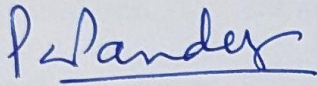
DEDICATED TO
MY PARENTS AND LOVED ONES

कर हिम्मत, बांध कमर, ले हुकम सब साथ।
पियू पास हो पहचान के, और छोड़ सब साथ॥

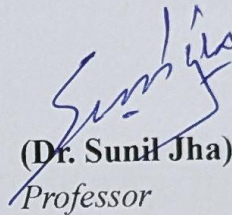
॥ सदा आनंद मंगल में रहिए ॥

Certificate

This is to certify that the thesis entitled '**Design and development of heel pad by using 3D printed bio-inspired lattice structure for reduction of plantar pressure**' submitted by **Mr. Patel Brijeshkumar Hasmukhbhai** to the Indian Institute of Technology Delhi, for the award of the degree of *Doctor of Philosophy*, is a record of the original bonafide research work carried out by him under my/our guidance and supervision. The results contained in it have not been submitted in part or full to any other institute or university for the award of any degree/diploma.



(Dr. Pulak Mohan Pandey)
IHFC Chair, Professor (HAG)
Department of Mechanical Engineering
Indian Institute of Technology Delhi



(Dr. Sunil Jha)
Professor
Department of Mechanical Engineering
Indian Institute of Technology Delhi

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(Patel Brijeshkumar Hasmukhbhai)

Abstract

The foot is subjected to different amplitudes of loads in day-to-day activities, and the acting loads apply pressure to the bottom surface of the foot. The bottom surface of the foot is called the plantar surface, and pressure acting on it is called the plantar pressure. The high plantar pressure is a primary factor contributing to conditions such as heel pain, foot ulcers, talalgia, and painful forefoot syndrome. In addition, people with high body mass frequently suffer from pain due to excessive walking or standing for a longer duration, which may also lead to health problems in the leg, knee and back. Apart from that high plantar pressure can contribute to further pain for elderly people. Naturally, the human foot contains fat paddings that provide cushioning and rebounding characteristics, but the foot alone cannot effectively overcome many of the loads and their effects encountered during regular activities. Functional customization of footwear midsoles can effectively reduce the diseases caused by high plantar pressure and provide more relaxation and comfort to patients. Functional customization in footwear can be reflected in the design of the midsole through the intervention of high energy absorbing materials that can effectively reduce the pressure acting on the foot. Traditionally, midsoles are manufactured using die casting and molding methods. The absorption properties of midsoles are controlled by varying structural parameters of pores such as pore size, pore shape, pore distribution etc. However, in traditional manufacturing methods, it is challenging to control the porosity parameters of midsoles. Therefore, the traditional manufacturing methods are not capable of manufacturing midsoles with high performance attributes. The need for such midsoles can be catered by intervention of light weight structures having high absorption properties such as lattice structures into midsole design.

The traditional lattice structures and their structural modifications were thoroughly explored by the researchers. It is important to develop new, innovative lattice structures, such as those inspired by biological materials, that could enhance performance attributes. In nature,

myriad patterns are available in plants and animals, out of which very few natural geometries are attended and still many biological structures are unattended. In order to fill this research gap, the novel lattice structures were designed by imitating the geometrical features of biological objects such as Helleborus petticoat flower and fish scale pattern into lattice strut configuration. The topological arrangement of struts and their connections in the cuboid were done by using elliptical curves to resemble geometrical features of biological systems into lattice strut configuration. Two variants of flower-based structures (namely FL4 and FL8) and one fish scale-based structure (namely FS) were designed. The bio-inspired lattice structures were fabricated from thermoplastic polyurethane material by using fused deposition modeling process.

It is important to determine energy absorption performance of developed bio-inspired structures. For that the static compression tests were conducted to study stress-strain behavior of the proposed structures in two different orientations, viz. orientation:1 (loading along z-axis) and orientation:2 (loading along x-axis). Furthermore, the mechanical responses, energy absorption characteristics, deformation behavior, and energy absorption diagrams are comprehensively examined for the proposed structures in both orientations. Finally, specific energy absorption (SEA) of proposed structures is compared with the SEA of other structures from the existing literature. The developed bio-inspired structures showed SEA in the range of 0.21-0.97 kJ/kg. In orientation:1, the SEA up to densification is 29.8% higher in FS, 298.5% higher in FL4, and 115.2% higher in FL8 structures compared to orientation:2. FL4 structure in orientation:1 exhibit higher SEA than honeycomb, origami honeycomb and gyroid structure of similar density, and FL8 structure in orientation:1 exhibit higher SEA than honeycomb and sea sponge inspired structures of similar density.

Cyclic compression test was performed on the developed bio-inspired structures. The stiffness, specific energy dissipation (SED), and specific damping capacity (SDC) were

determined for two orientations viz., orientation:1 and orientation:2. The developed structures exhibited higher stiffness, SED, and SDC in orientation:1 than in orientation:2. The stiffness, SED, and SDC decrease with deformation, i.e., these properties are lower for the 21st cycle compared to the 1st cycle. The decrease in properties is higher for the first six cycles, and properties become stable after the 15th cycle for all structures. Most of the published work incorporated lattice structures into the insoles. Very few attempts have been made to develop midsoles with 3D printed lattice structures. In order to fill this gap, the heel pads were developed by using bio-inspired lattice structures and the plantar pressure measurement was done for standing and walking conditions. The experimental findings of plantar pressure measurement and energy absorption diagrams form the basis for selecting the best structure for heel pad applications. The selection of lattice structures for midsole applications not only depends on energy absorption capacity but it also depends on the stress at which energy absorption takes place. From the plantar pressure measurement and energy absorption diagrams, it was found that the FS structure in orientation:2 is the most suitable structure for midsole applications.

The FS structure in orientation:2 was selected for further analysis. To the best of author's knowledge, no work has been reported on the development of statistical models to predict responses for bio-inspired structures. In order to fill this gap, statistical modelling was done to predict stiffness, SEA, and plantar pressure for bio-inspired lattice structure. The effect of unit cell structural parameters such as length of unit cell, strut height, and strut diameter on the responses namely stiffness, SEA, and plantar pressure were investigated. The experiments were performed as per response surface methodology (RSM), and response data were analysed using Analyses of Variance (ANOVA). Further, the optimized unit cell structural parameters were obtained for minimization of plantar pressure using MATLAB. The properties such as stiffness, SEA, and plantar pressure were found to be decreasing as the length of unit cell and

strut height were increased. Whereas these properties were found to be increasing with an increase in strut diameter. Finally, the case study was performed to compare performance of optimized heel pad with commercial footwear and other 3D printed structures used in midsole applications from the existing literature. The 3D printed bio-inspired heel pad at optimum conditions showed 19.46% reduction in plantar pressure compared to commercial footwear. The weight of the optimized heel pad was found to be 26.08% lower than the commercial footwear sole. The 3D printed bio-inspired heel pad at optimized conditions provided the highest percentage reduction in plantar pressure compared to other structures used in midsole application from existing literature.

सार

दिन-प्रतिदिन की गतिविधियों में पैर को विभिन्न आयामों के भार के अधीन किया जाता है, और अभिनय भार पैर की निचली सतह पर दबाव डालता है। पैर की निचली सतह को तल की सतह कहा जाता है, और उस पर लगने वाले दबाव को तल का दबाव कहा जाता है। उच्च तल का दबाव एड़ी में दर्द, पैर के अल्सर, टैलेल्जिया और दर्दनाक फोरफुट सिंड्रोम जैसी स्थितियों में योगदान देने वाला एक प्राथमिक कारक है। इसके अलावा, अधिक वजन वाले लोग अक्सर अत्यधिक चलने या लंबे समय तक खड़े रहने के कारण दर्द से पीड़ित होते हैं, जिससे पैर, घुटने और पीठ में स्वास्थ्य समस्याएं भी हो सकती हैं। इसके अलावा उच्च तल का दबाव बुजुर्ग लोगों के लिए और अधिक दर्द में योगदान कर सकता है। स्वाभाविक रूप से, मानव पैर में वसा पैडिंग होती है जो कुशनिंग और रिबाउंडिंग विशेषताएं प्रदान करती है, लेकिन अकेले पैर नियमित गतिविधियों के दौरान आने वाले कई भार और उनके प्रभावों को प्रभावी ढंग से दूर नहीं कर सकता है। फुटवियर मिडसोल का कार्यात्मक अनुकूलन उच्च प्लांटर दबाव के कारण होने वाली बीमारियों को प्रभावी ढंग से कम कर सकता है और रोगियों को अधिक आराम और आराम प्रदान कर सकता है। जूते में कार्यात्मक अनुकूलन उच्च ऊर्जा अवशोषित सामग्री के हस्तक्षेप के माध्यम से मिडसोल के डिजाइन में परिलक्षित हो सकता है जो पैर पर अभिनय करने वाले दबाव को प्रभावी ढंग से कम कर सकता है। परंपरागत रूप से, मिडसोल का निर्माण डार्ड कास्टिंग और मोल्डिंग विधियों का उपयोग करके किया जाता है। मध्य तलवों के अवशोषण गुणों को छिद्रों के विभिन्न संरचनात्मक मापदंडों जैसे छिद्र आकार, छिद्र आकार, छिद्र वितरण आदि द्वारा नियंत्रित किया जाता है। हालांकि, पारंपरिक विनिर्माण विधियों में, मध्य तलवों के छिद्र मापदंडों को नियंत्रित करना चुनौतीपूर्ण है। इसलिए, पारंपरिक विनिर्माण विधियां उच्च प्रदर्शन विशेषताओं वाले मिडसोल का निर्माण करने में सक्षम नहीं हैं। ऐसे मिडसोल की आवश्यकता को उच्च अवशोषण गुणों वाले हल्के वजन संरचनाओं के हस्तक्षेप से पूरा किया जा सकता है जैसे कि मिडसोल डिजाइन में जाली संरचनाएं।

शोधकर्ताओं द्वारा पारंपरिक जाली संरचनाओं और उनके संरचनात्मक संशोधनों का गहन अध्ययन किया गया। नई, नवीन जाली संरचनाएं विकसित करना महत्वपूर्ण है, जैसे कि जैविक सामग्रियों से प्रेरित, जो प्रदर्शन विशेषताओं को बढ़ा सकती हैं। प्रकृति में, पौधों और जानवरों में असंख्य पैटर्न उपलब्ध हैं, जिनमें से बहुत कम प्राकृतिक ज्यामिति पर ध्यान दिया जाता है और अभी भी कई जैविक संरचनाएं अप्राप्य हैं। इस शोध अंतर को भरने के लिए, हेलेबोरस पेटीकोट फूल और मछली स्केल पैटर्न जैसी जैविक वस्तुओं की ज्यामितीय विशेषताओं को जाली स्ट्रट कॉन्फ़िगरेशन में अनुकरण करके उपन्यास जाली संरचनाओं को डिजाइन किया गया था। स्ट्रट्स की टोपोलॉजिकल व्यवस्था और क्यूबॉइड में उनके कनेक्शन को जाली स्ट्रट कॉन्फ़िगरेशन में जैविक प्रणालियों की ज्यामितीय विशेषताओं के समान अण्डाकार वक्रों का उपयोग करके किया गया था। फूल-आधारित संरचनाओं के दो प्रकार (अर्थात् FL4 और FL8) और एक मछली स्केल-आधारित संरचना (अर्थात् FS) डिज़ाइन किए गए थे। फ़्यूज़्ड डिपोजिशन मॉडलिंग प्रक्रिया का उपयोग करके थर्मोप्लास्टिक पॉलीयूरेथेन सामग्री से जैव-प्रेरित जाली संरचनाएं बनाई गईं।

विकसित जैव-प्रेरित संरचनाओं के ऊर्जा अवशोषण प्रदर्शन को निर्धारित करना महत्वपूर्ण है। इसके लिए दो अलग-अलग अभिविन्यासों में प्रस्तावित संरचनाओं के तनाव-तनाव व्यवहार का अध्ययन करने के लिए स्थैतिक संपीड़न परीक्षण आयोजित किए गए थे। ओरिएंटेशन:1 (जेड-अक्ष के साथ लोड हो रहा है) और ओरिएंटेशन:2 (एक्स-अक्ष के साथ लोड हो रहा है)। इसके अलावा, दोनों अभिविन्यासों में प्रस्तावित संरचनाओं के लिए यांत्रिक प्रतिक्रियाओं, ऊर्जा अवशोषण विशेषताओं, विरूपण व्यवहार और ऊर्जा अवशोषण आरेखों की व्यापक जांच की जाती है। अंत में, प्रस्तावित संरचनाओं के विशिष्ट ऊर्जा अवशोषण (एसईए) की तुलना मौजूदा साहित्य से अन्य संरचनाओं के एसईए के साथ की जाती है। विकसित जैव-प्रेरित संरचनाओं ने एसईए को 0.21-0.97 केजे/किग्रा की सीमा में दिखाया। अभिविन्यास:1 में, सघनीकरण तक एसईए अभिविन्यास:2 की तुलना में एफएस में 29.8% अधिक, एफएल4 में 298.5% अधिक, और एफएल8 संरचनाओं में 115.2% अधिक है। अभिविन्यास में FL4 संरचना:1 मधुकोश की

तुलना में उच्च SEA प्रदर्शित करती है, ओरिगेमी मधुकोश और समान घनत्व की जाइरॉइड संरचना, और अभिविन्यास में FL8 संरचना:1 समान घनत्व वाले मधुकोश और समुद्री स्पंज से प्रेरित संरचनाओं की तुलना में उच्च SEA प्रदर्शित करती है।

विकसित जैव-प्रेरित संरचनाओं पर चक्रीय संपीड़न परीक्षण किया गया। कठोरता, विशिष्ट ऊर्जा अपव्यय (एसईडी), और विशिष्ट अवमंदन क्षमता (एसडीसी) दो अभिविन्यासों अर्थात अभिविन्यास:1 और अभिविन्यास:2 के लिए निर्धारित की गई थी। विकसित संरचनाओं ने अभिविन्यास:2 की तुलना में अभिविन्यास:1 में उच्च कठोरता, एसईडी और एसडीसी का प्रदर्शन किया। विरूपण के साथ कठोरता, एसईडी और एसडीसी कम हो जाती है, यानी, ये गुण पहले चक्र की तुलना में 21वें चक्र के लिए कम हैं। पहले छह चक्रों के लिए गुणों में कमी अधिक होती है, और सभी संरचनाओं के लिए 15वें चक्र के बाद गुण स्थिर हो जाते हैं। अधिकांश प्रकाशित कार्यों में इनसोल में जाली संरचनाओं को शामिल किया गया है। 3डी प्रिंटेड जाली संरचनाओं के साथ मिडसोल विकसित करने के बहुत कम प्रयास किए गए हैं। इस अंतर को भरने के लिए, जैव-प्रेरित जाली संरचनाओं का उपयोग करके एड़ी पैड विकसित किए गए थे और खड़े होने और चलने की स्थिति के लिए तल का दबाव माप किया गया था। तल के दबाव माप और ऊर्जा अवशोषण आरेख के प्रयोगात्मक निष्कर्ष एड़ी पैड अनुप्रयोगों के लिए सर्वोत्तम संरचना का चयन करने का आधार बनाते हैं। मिडसोल अनुप्रयोगों के लिए जाली संरचनाओं का चयन न केवल ऊर्जा अवशोषण क्षमता पर निर्भर करता है बल्कि यह उस तनाव पर भी निर्भर करता है जिस पर ऊर्जा अवशोषण होता है। तल के दबाव माप और ऊर्जा अवशोषण आरेखों से, यह पाया गया कि अभिविन्यास में एफएस संरचना: 2 मिडसोल अनुप्रयोगों के लिए सबसे उपयुक्त संरचना है।

आगे के विश्लेषण के लिए ओरिएंटेशन:2 में एफएस संरचना का चयन किया गया था। लेखक की सर्वोत्तम जानकारी के अनुसार, जैव-प्रेरित संरचनाओं के लिए प्रतिक्रियाओं की भविष्यवाणी करने के लिए सांख्यिकीय मॉडल के विकास पर कोई काम रिपोर्ट नहीं किया गया है। इस अंतर को भरने के लिए, जैव-

प्रेरित जाली संरचना के लिए कठोरता, एसईए और तल के दबाव की भविष्यवाणी करने के लिए सांख्यिकीय मॉडलिंग की गई थी। यूनिट सेल संरचनात्मक मापदंडों जैसे यूनिट सेल की लंबाई, स्ट्रूट ऊंचाई और स्ट्रूट व्यास के प्रतिक्रियाओं पर कठोरता, एसईए और प्लांटर दबाव के प्रभाव की जांच की गई। प्रयोग प्रतिक्रिया सतह पद्धति (आरएसएम) के अनुसार किए गए थे, और प्रतिक्रिया डेटा का विश्लेषण एनालिसिस ऑफ वेरिएंस (एनोवा) का उपयोग करके किया गया था। इसके अलावा, MATLAB का उपयोग करके तल के दबाव को कम करने के लिए अनुकूलित यूनिट सेल संरचनात्मक पैरामीटर प्राप्त किए गए थे। यूनिट सेल की लंबाई और स्ट्रूट की ऊंचाई बढ़ने के कारण कठोरता, एसईए और तल का दबाव जैसे गुण कम होते पाए गए। जबकि ये गुण स्ट्रूट व्यास में वृद्धि के साथ बढ़ते हुए पाए गए। अंत में, मौजूदा साहित्य से मिडसोल अनुप्रयोगों में उपयोग किए जाने वाले वाणिज्यिक जूते और अन्य 3 डी मुद्रित संरचनाओं के साथ अनुकूलित एड़ी पैड के प्रदर्शन की तुलना करने के लिए केस अध्ययन किया गया था। इष्टतम परिस्थितियों में 3डी प्रिंटेड बायो-प्रेरित हील पैड ने वाणिज्यिक जूते की तुलना में तल के दबाव में 19.46% की कमी दिखाई। अनुकूलित हील पैड का वजन वाणिज्यिक फुटवियर सोल की तुलना में 26.08% कम पाया गया। मौजूदा साहित्य से मिडसोल एप्लिकेशन में उपयोग की जाने वाली अन्य संरचनाओं की तुलना में अनुकूलित परिस्थितियों में 3डी प्रिंटेड बायो-प्रेरित हील पैड ने प्लांटर दबाव में उच्चतम प्रतिशत की कमी प्रदान की।

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Acronym

ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
ANOVA	Analysis of Variance
BCC	Body Centred Cubic
BCT	Body Centred Tetragonal
CAD	Computer Aided Design
CCD	Central Composite Design
DAQ	Data Acquisition
DIW	Direct Ink Writing
DNA	Deoxyribonucleic Acid
EVA	Ethylene Vinyl Acetate
FCC	Face Centred Cubic
FDM	Fused Deposition Modeling
FSR	Force Sensing Resistor
GRF	Ground Reaction Force
MEX	Material Extrusion
MJF	Multi Jet Fusion
NPR	Negative Poisson's Ratio
PC	Polycarbonate
PETG	Polyethylene Terephthalate Glycol
PLA	Polylactic Acid
PU	Polyurethane
RD	Relative density

RSM	Response Surface Methodology
SC	Simple Cubic
SDC	Specific Damping Capacity
SEA	Specific Energy Absorption
SED	Specific Energy Dissipation
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SoC	Standard of Care
SU	Sea Urchin
TO	Topology Optimized
TPMS	Triply Periodic Minimal Surface
TPU	Thermoplastic Polyurethane
UTM	Universal Testing Machine

Nomenclature

F2BCC	Combination of FCC and BCC structure
FL4	Flower inspired structure having four struts
FL8	Flower inspired structure having eight struts
FS	Fish scale inspired structure
1DF	One-dimensional flower
2DF	Two-dimensional flower
EA	Energy absorption capacity
ε_d	Onset strain of densification
σ	Stress
ε	Strain
ε_y	Yield point strain
η	Energy absorption efficiency
σ_p	Peak stress
σ_{pl}	Mean plateau stress
ρ^*	Density of structure
m	Mass
V	Volume
E	Elastic modulus
ΔW	Energy dissipation during cyclic compression
W	Energy absorbed during loading
Y	Response output
β_i	Coefficients for linear terms
β_{ij}	Coefficients for interaction terms

β_0	Interception coefficient
S	Stiffness
E_s	Specific energy absorption
P	Plantar pressure