iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL
FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 Issue: V Month of publication: May 2025

DOI: https://doi.org/10.22214/ijraset.2025.70972

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue V May 2025- Available at www.ijraset.com

Therapeutic 3D-Printed Insole with Vibration Sensing

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Abstract: Foot-related conditions such as diabetic nephropathy, plantar fasciitis, and musculoskeletal disorders can significantly impair mobility and increase the risk of foot ulcers and falls. This study presents the development of a customization, therapeutic 3D-printed insole integrated with vibration sensing technology to address these challenges. Designed using Sketch-up and fabricated with TPU material through precision slicing in UltimakerCura, the insole is tailored to the user's foot anatomy for optimal fit and comfort. A vibration motor and sensor are embedded to monitor pressure changes, foot movement, and gait abnormalities, providing real-time feedback for preventive care and rehabilitation. Post-processing techniques enhance durability and usability. By combining digital fabrication with smart biomechanics, this innovative insole offers a cost-effective, non-invasive solution for continuous foot health monitoring, supporting personalized healthcare, fall prevention, and athletic performance optimization.

Keywords: 3D-printed insole-Vibration sensing technology-Foot health monitoring-Diabetic neuropathy-Musculoskeletal disorder-Real-time feedback-TPU material. prevention-rehabilitation support.

I. INTRODUCTION

Foot health plays a vital role in maintaining overall mobility, balance, and quality of life. Conditions such as diabetic nephropathy, plantar fasciitis, and musculoskeletal disorders often lead to discomfort, impaired gait, reduced sensory feedback, and increased susceptibility to falls and pressure ulcers. These challenges necessitate effective, personalized solutions that not only provide comfort but also enable continuous monitoring and therapeutic support.

Advancements in additive manufacturing and wearable sensor technology have paved the way for innovative healthcare solutions. Among them, 3D-printed insoles offer significant advantages by allowing precise customization based on individual foot anatomy and bio-mechanical needs. Integrating smart sensors into such insoles enhances their functionality, transforming them into powerful tools for real-time gait analysis, foot pressure monitoring, and preventive care.

This study focuses on the development of a 3D-printed insole embedded with vibration sensing capabilities, designed specifically to improve foot health and provide therapeutic feedback. By utilizing software such as Sketch-up for design and UltimakerCura for slicing, the insole is fabricated using flexible TPU material, known for its durability and comfort. The integration of a vibration motor and sensor enables dynamic tracking of foot movements and abnormalities, supporting early detection and intervention in at-risk individuals. This research aims to bridge the gap between digital fabrication, smart sensing, and personalized therapy, offering a cost-effective and non-invasive solution for long-term foot care.

II. RELATED WORKS

1) *Effects of Customized 3D-Printed Insoles in Patients with Foot-Related Musculoskeletal Ailment-A Survey-Based Study*

A study involving 200 patients evaluated foot health issues through pressure analysis and clinical assessments, focusing on conditions like diabetic nephropathy, plantar fasciitis, flat feet, and musculoskeletal imbalances. To address these concerns, customized therapeutic insoles were designed using SolidWork software and 3D printed with TPU material, ensuring flexibility, durability, and optimal pressure distribution.

The insoles were tailored to individual pediatric needs, adjusting for density, arch height, and heel support. Patients used them daily for 6 to 18 months, and their effectiveness was assessed based on pain relief, improved pressure redistribution, walking comfort, and durability. Clinical evaluations and patient feedback confirmed that the 3D-printed insoles significantly enhanced foot comfort, reduced strain, and helped prevent complications, highlighting their potential as a cost-effective and personalized solution for long-term pediatric care.

2) The effects of vibrating shoe insoles on standing balance, walking, and ankle-foot muscle activity in adults with diabetic peripheral neuropathy

A randomized cross-over study was conducted with 18 adults diagnosed with diabetic peripheral neuropathy (DPN) to assess the effects of vibrating insoles on balance and gait. Participants underwent standing balance assessments using a Bertec® force platform, gait analysis on a GAITRite® walkway, and muscle activity measurements via electromyography (EMG). Each participant tested both vibrating and non-vibrating insoles on separate days, allowing for a comparative evaluation of their impact on stability and walking patterns. The study aimed to determine whether vibration-enhanced insoles could improve postural control and gait mechanics in individuals with DPN, potentially offering a therapeutic intervention for balance impairments and fall prevention.

3) 3D Printing of Individual Running Insoles – A Case Study

A study was conducted to develop and evaluate personalized 3D-printed insoles using advanced scanning and digital design techniques. A 3D scan of the foot was captured using the Artec Eva scanner, ensuring precise anatomical mapping for a custom fit. The digital models were then designed using Gensole EasyCAD software, allowing for individualized adjustments to arch support, pressure distribution, and overall foot alignment. Four prototype insoles were fabricated using flexible TPU material on a Prusa i3 MK3S 3D printer, chosen for its durability, flexibility, and shock-absorbing properties. A recreational runner tested the insoles over a three-month period, during which their comfort, impact absorption, and effectiveness in reducing foot pain were evaluated. The runner provided feedback on fit, cushioning, and long-term wearability, while qualitative assessments were made to determine improvements in gait and running efficiency. The study demonstrated that 3D-printed customized insoles can provide enhanced comfort and support, making them a promising solution for athletes and individuals requiring personalized orthotic interventions.

4) Comparative Efficacy of 3D-Printed Insoles in Managing Common Foot Conditions: A Review

A comprehensive literature review was conducted to analyse the effectiveness of 3D-printed insoles in treating various foot conditions compared to traditional insoles. Relevant studies were systematically collected from MEDLINE, Embase, Scopus, and the Cochrane Library, ensuring a broad and high-quality evidence base. The review focused on three primary conditions: flexible flatfoot, diabetic foot ulcers, and plantar fasciitis, which are commonly associated with pain, improper weight distribution, and mobility impairments. Key factors such as pressure redistribution, arch support, pain relief, durability, and patient satisfaction were analyzed across multiple studies. The findings indicated that 3D-printed insoles offer superior customization, better pressure offloading, and improved biomechanical correction, making them a promising alternative to conventional insoles. The ability to precisely tailor insole geometry using digital modelling and additive manufacturing provides enhanced comfort and therapeutic benefits, particularly for individuals requiring long-term podiatric intervention. The review highlights the growing potential of 3D printing technology in personalized orthotic care, offering a cost-effective and innovative approach to foot health management.

5) 3D Printed Soft and Flexible Insole with Intrinsic Pressure Sensing Capability

A flexible insole with embedded capacitive pressure sensors was developed using multimaterial 3D printing, combining Thermoplastic Polyurethane (TPU) for flexibility and conductive thermoplastic for sensing capabilities. The insole was designed to provide real-time pressure feedback for applications in gait analysis and foot health monitoring. Its pressure response and durability were evaluated through 1,000 compression cycles at 30 kPa, ensuring reliability and long-term functionality. The insole was then integrated with electronic components, enabling continuous pressure monitoring and data transmission. To validate its performance, it was tested in gait analysis experiments, where it successfully captured dynamic pressure variations, weight distribution, and walking patterns. The study demonstrated that multilaterial 3D printing enables the creation of advanced, sensor-integrated insoles, offering a promising solution for personalized foot health monitoring, rehabilitation, and biomechanical research.

6) Development of 3D-Printed Orthopedic Insoles for Patients with Diabetes and Evaluation with Electronic Pressure Sensors

A study was conducted to develop and evaluate 3D-printed insoles using advanced 3D scanning, digital modeling, and additive manufacturing techniques. Foot scans were obtained to create precise anatomical models, which were digitally processed using Gensole software for custom insole design. The fabrication process utilized flexible polymers, including thermoplastic polyether-polyurethane and TPU polyester-based polymer, chosen for their shock absorption, flexibility, and durability. To assess their effectiveness, plantar pressure distribution was measured during walking trials using electronic pressure sensors, capturing variations in foot load and pressure redistribution.

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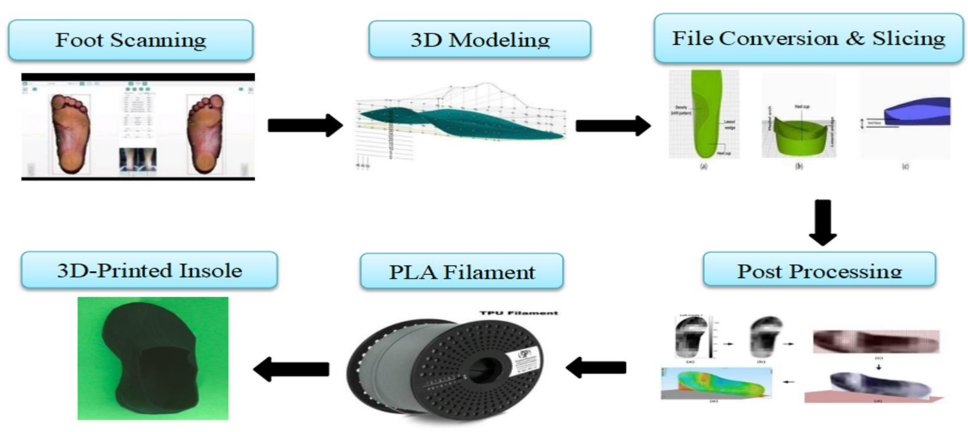
The 3D-printed insoles were compared against standard insoles following a clinical evaluation protocol, analyzing parameters such as comfort, pressure offloading, gait improvement, and biomechanical alignment. The findings demonstrated that custom 3D-printed insoles provided enhanced pressure relief and improved walking mechanics, highlighting their potential as an innovative, patient-specific alternative to traditional orthotic solutions.

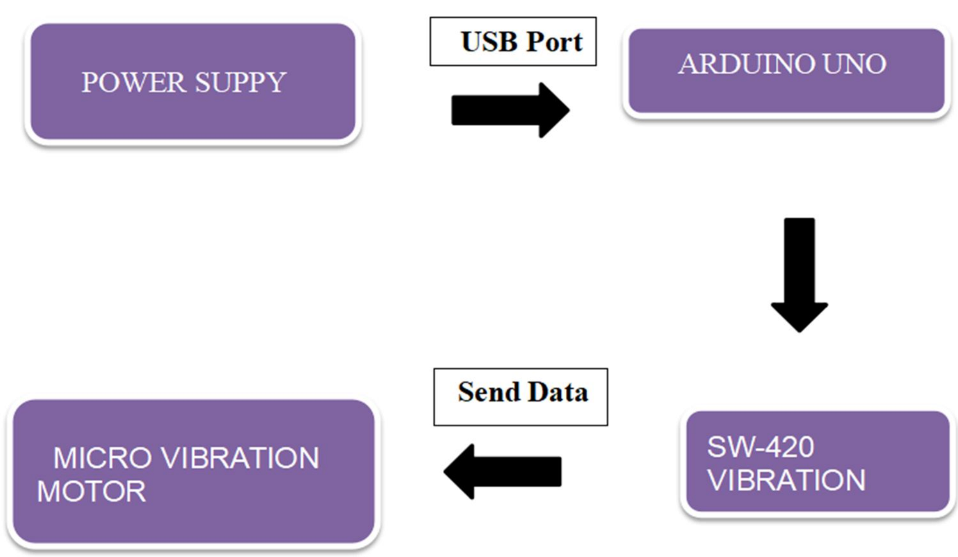
III. METHODOLOGY

Vibration therapy to the foot involves a systematic process designed to deliver consistent mechanical stimulation to enhance therapeutic outcomes. A micro vibration motor was selected for its compact size and ability to generate low-frequency vibrations (typically between 80 Hz and 120 Hz), which are known to stimulate circulation and nerve endings. The motor was positioned strategically beneath the arch and heel regions of the foot to target pressure points and maximize coverage. A power source, such as a rechargeable battery, was connected to regulate the motor's operation, controlled manually or by a basic circuit switch. To ensure comfort and safety, the motor was embedded in a soft, ergonomically contoured layer that allows even distribution of vibrations without causing pressure or discomfort. The device was tested on users under controlled time intervals (10–15 minutes daily), and feedback was recorded regarding changes in pain, comfort, and circulation. Observations were supported by user-reported outcomes, which confirmed improvements in muscle relaxation and a noticeable reduction in foot fatigue. This structured methodology supports the therapeutic potential of localized vibration in managing foot-related disorders and maintaining foot health.

IV. BLOCK DIAGRAM



Block diagram 1:3D-Printed Insole Design Method



Block diagram 2: Vibration Sensing Method

V. HARDWARE DESCRIPTION

A. Arduino

The Arduino UNO is a popular open-source microcontroller board based on the ATmega328P chip. It features 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz quartz crystal, a USB connection, a power jack, an ICSP header, and a reset button. It operates at 5V with a recommended input voltage of 7–12V and can handle a maximum of 6–20V. The board has 32 KB of flash memory for storing code (with 0.5 KB used by the bootloader), 2 KB of SRAM, and 1 KB of EEPROM. It supports communication via UART, SPI, and I2C protocols and is programmed using the Arduino IDE, making it ideal for beginners and prototyping in electronics and embedded systems.

B. Micro Vibration Motor

A micro vibration motor is a precision-engineered miniature actuator designed to deliver tactile feedback through controlled oscillations, commonly used in compact electronic systems and wearable therapeutic technologies. The most prevalent variant, the Eccentric Rotating Mass (ERM) motor, operates by spinning a small, off-center weight attached to a high-speed micro DC motor shaft, thereby creating subtle yet effective vibrations. Typically powered at 3V DC, these motors function within a voltage range of 2.5V to 3.7V, consuming around 90 to 100 mA of current and achieving speeds up to 12,000 RPM, which translates into perceptible vibration intensities of 0.8 to 1.2 G. Despite their tiny footprint—often no larger than 3–10 mm in diameter and weighing less than 2 grams—they are built for consistent performance, capable of delivering reliable haptic feedback in space-constrained environments. Their silent operation, combined with versatile mounting options such as adhesive pads or solderable leads, makes them ideal for integration into next-generation rehabilitative devices, smart footwear, alert systems, and biomedical monitoring tools. The ability of these motors to transform electrical energy into mechanical vibration with high efficiency underscores their role as a crucial component in human-centered design, especially where sensory stimulation, comfort, and real-time responsiveness are vital.

C. SW-420 Vibration Sensor

The SW-420 vibration sensor is a compact, cost-effective module designed to detect vibrations and shocks in its environment. It consists of a spring-type vibration switch and a comparator circuit for signal processing. The sensor operates at a voltage range of 3.3V to 5V and outputs a digital signal: HIGH when no vibration is detected and LOW when vibration occurs. It features an onboard LM393 comparator for stable signal output, an adjustable sensitivity via potentiometer, and indicator LEDs for power and output status. The sensor module is highly responsive to sudden movements and is commonly used in security systems, vibration-triggered alerts, motor monitoring, and interactive feedback devices. It is compatible with microcontrollers like Arduino and Raspberry Pi, making it suitable for both prototyping and embedded applications.

VI. SOFTWARE DESCRIPTION

A. Arduino IDE

The Arduino development environment contains a text editor or writing code, a message area text console, a tool bar with buttons for common functions, and a series of menus. It connects to the Arduino hardware to upload programs and communicate with them.

B. SolidWorks

SolidWorks is a powerful, feature-rich computer-aided design (CAD) and computer-aided engineering (CAE) software developed by Dassault Systèmes, widely used for 3D modeling, product design, and simulation. It runs on Windows-based systems and supports both 32-bit and 64-bit architectures (with modern versions primarily optimized for 64-bit). The software requires a minimum of 16 GB RAM (32 GB recommended for complex assemblies), a multi-core processor (Intel i7 or higher preferred), and a professional-grade graphics card such as NVIDIA Quadro or AMD FirePro, certified by SolidWorks for optimal performance. SolidWorks includes modules for part modeling, assembly design, 2D drawing, simulation (FEA/CFD), motion analysis, rendering (PhotoView 360), sheet metal, weldments, and surface modeling.

It supports a variety of file formats including .SLDPRT, .SLDASM, .SLDDRW, .STEP, .IGES, .STL, and .DXF, allowing seamless integration with 3D printers and other CAD platforms. The user interface is intuitive, featuring drag-and-drop components, parametric design capabilities, and integrated design validation tools, making it ideal for engineers, designers, and researchers working on mechanical, biomedical, and industrial projects.

C. STL File

The STL (Stereolithography) file format is a widely used file type for 3D printing and computer-aided manufacturing. It represents the surface geometry of a 3D object without including color, texture, or other attributes. STL files store information as a collection of triangular facets, where each triangle is defined by three vertices and a normal vector that indicates the direction of the face. The format supports both ASCII and binary encoding, with the binary version being more compact and faster to process. STL files do not contain scale or unit information, so it's crucial to ensure that the design software and slicer use the same units (usually millimeters or inches). Due to its simplicity and compatibility, STL is the standard format for most 3D printers and slicing software like Cura, PrusaSlicer, and Simplify3D, making it essential for rapid prototyping and additive manufacturing workflows. However, it does not support advanced features like material properties or assemblies, which are available in more modern formats such as 3MF or AMF.

D. ULTIMAKERCURA

Ultimaker Cura is a widely used open-source slicing software designed for preparing 3D models for printing, compatible with a variety of FDM/FFF 3D printers. Developed by Ultimaker, it supports a broad range of 3D file formats including .STL, .OBJ, .3MF, and .AMF, and converts them into G-code instructions understood by 3D printers. Cura is compatible with Windows (7 or newer), macOS (10.14 or newer), and Linux (Ubuntu 18.04 or newer). It requires a 64-bit system, with at least 4 GB of RAM (8 GB or more recommended), a dual-core processor, and a graphics card supporting OpenGL 4.1 or higher. Cura features customizable print settings, including layer height, print speed, temperature, support structures, infill patterns, and build plate adhesion types. It provides beginner-friendly “recommended” modes and advanced customization for expert users. Cura also includes features like real-time preview, print time estimation, plugin support, printer profile management, and integration with CAD tools like SolidWorks via plugins. It supports both Ultimaker printers and a wide range of third-party printers, making it a flexible and powerful tool for students, hobbyists, researchers, and professionals in the 3D printing field.

E. Programming

NodeMCU programming refers to the process of writing code and developing applications for NodeMCU, which is a low-cost open-source IoT platform based on the ESP8266 Wi-Fi module. The NodeMCU board integrates the ESP8266 chip with additional hardware and an easy-to-use firmware, making it a popular choice for Internet of Things (IoT) projects.NodeMCU can be programmed using the Lua scripting language, but it is more commonly programmed using the Arduino IDE with the help of the Arduino core for ESP8266. This allows developers to use the familiar Arduino programming environment and language, which is based on C/C++.o program NodeMCU using the Arduino IDE, you need to install the ESP8266 board support package. This package includes the necessary tools and libraries to program the NodeMCU board. Once installed, you can select NodeMCU as your target board in the Arduino IDE.Once the code is written, it needs to be uploaded to the NodeMCU board. This is done through the USB interface, and the Arduino IDE provides a convenient way to upload the code to the board.NodeMCU programming enables developers to create IoT projects quickly and efficiently using the ESP8266 module. It's a versatile platform that has gained popularity due to its ease of use, low cost, and widespread community support.

VII. CONCLUSION

Vibration therapy to the foot has proven to be an effective, non-invasive method for enhancing blood circulation, reducing pain, and promoting muscular relaxation. Through the application of targeted, low-frequency mechanical stimulation, this approach supports natural healing processes and improves comfort, particularly for individuals experiencing chronic foot conditions such as neuropathy, plantar fasciitis, arthritis, and fatigue due to extended standing or walking. It stimulates sensory receptors and mechanoreceptors in the foot sole, aiding in the restoration of proprioceptive feedback and balance control, which are often impaired in patients with neurological or musculoskeletal disorders.

Furthermore, vibration therapy helps reduce inflammation, alleviate stiffness, and increase local tissue oxygenation, contributing to faster recovery and improved foot function. Its simplicity, safety, and drug-free nature make it a practical therapeutic solution for daily foot care, preventive health, post-exercise recovery, and long-term wellness. The integration of vibration therapy into smart insoles or foot platforms also enables personalized intensity adjustment and real-time monitoring, further enhancing its clinical and home-based applications.

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