Guangdong University of Technology Human Subject Experiment Ethics Review Form

Achievement Title	Augment Cushioning and Stability in Jump-Landing: Biomechanical Assessment of Auxetic Lattice Structures in Athletic Footwear Midsoles
Achievement Accepting Unit	Scientific Reports
Applicant and Affiliation	Jifa Zhang School of Art and Design, Guangdong University of Technology
Purpose and Scheme of Human Experiment	**I. Experimental Objectives** Evaluate and compare the biomechanical performance of 3D-printed shoe midsoles with different internal geometric structures (specifically auxetic structures with negative Poisson's ratios) under dynamic impact. By contrasting with traditional polyurethane (PU) midsoles and non-auxetic lattice midsoles, investigate the potential advantages of auxetic structures in cushioning, shock absorption, and motion stability. Specific research objectives include: (1) Investigation of Structural Effects Under strictly controlled conditions of material volume, density, and overall dimensions, identify the influence of lattice geometry (primarily internal angles) on midsole performance, focusing on the differences between 60° and 75° auxetic structures versus the 90° traditional structure. (2) Quantification of Biomechanical Performance Quantify key biomechanical parameters of different midsoles during high-intensity impact (vertical jump-landing) through standardized subject wear trials.

II. Experimental Protocol

(1) Design of Shoe Midsoles Used in the Experiment

This study designed and manufactured midsoles featuring re-entrant auxetic lattice structures (with internal angles of 60° and 75°) and a conventional lattice structure (90° internal angle), using a standard PU midsole as a control. All four experimental midsoles were size EU 42. Since midsole thickness may affect ground reaction forces and vertical impact loading rates, all experimental midsoles were ensured to have identical thickness. Each lattice-structured midsole consisted of two layers of uniformly arranged lattice units in the longitudinal direction.

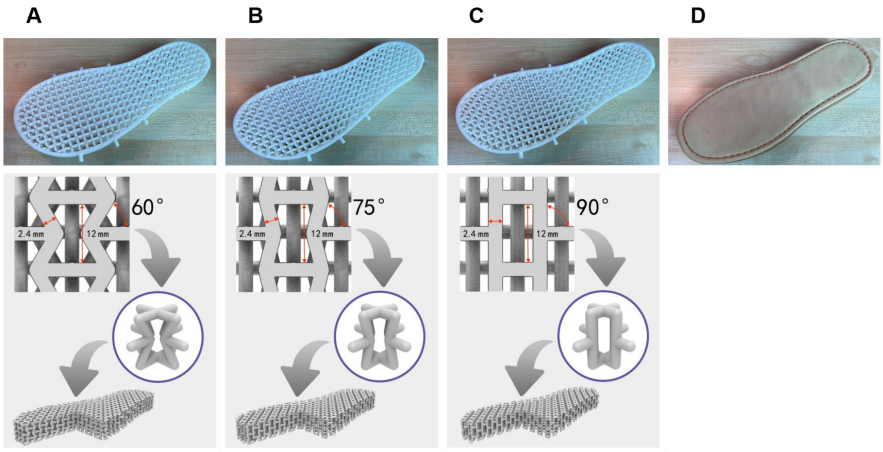

Figure 1. Designs of the three lattice midsoles (A, B, C) and the PU midsole control (D): (A) Auxetic 60° midsole. (B) Auxetic 75° midsole. (C) Non-auxetic 90° midsole. (D) PU midsole.

The 3D structures and geometric characteristics of the lattice units for the three designed midsole types are shown in Figure 1. Each lattice unit featured ribs with a diameter of 2.4 mm and a height of 12 mm. Based on multiple sample fabrication attempts, setting the rib height of the lattice unit to 12 mm was determined to provide sufficient space for lattice deformation when the shoe

	midsole is under compression. To isolate structural effects, the three lattice midsoles maintained nearly identical material volumes (125 ± 0.88 cm^3) and constant volume occupancy ratios, effectively controlling relative density variables. Specimens were digitally modeled via parametric algorithms in Rhino 7® with Grasshopper® 3.5, then additively manufactured using Tiertime UP300 Fused Deposition Modeling (FDM) equipment. Fabrication employed elastic thermoplastic polyurethane (TPU 95A) under precise deposition control—achieving nozzle positioning accuracies of (x, y, z) = (2, 2, 0.5) μm and a layer resolution of 0.1 mm. (2) Research Process The study first conducted plantar pressure system testing from January 4th to 14th, 2026, to obtain real plantar biomechanical parameters, including Center of Pressure (CoP) displacement, impact force, contact area, and plantar pressure. Since measurements of plantar biomechanical parameters (e.g., impact force) may be affected by individual motor skills, Finite Element Analysis (FEA) was also performed to validate the effectiveness of plantar pressure measurement results and ensure that individual physical characteristics did not influence experimental outcomes. (3) Subjects Given that the experimental shoe prototypes used in this study are currently only available in size EU 42, we recruited volunteers with matching foot sizes. Since females with size 42 feet are rare and often tend to be taller or heavier, and significant differences in height and weight could introduce large errors into the experimental results, only male subjects were recruited. Twenty healthy male subjects wearing standardized EU-42 footwear were recruited based on stringent inclusion criteria: 1) no history of lower limb

orthopedic surgery or fractures; 2) pain-free locomotion; 3) no musculoskeletal deformities; 4) physiologically normal gait patterns; 5) non-athlete status with no specialized motor training experience. Accordingly, participants aged 19–23 years had an average height of (169 ± 1.9) cm, average weight of (69 ± 4.6) kg, and average foot length of (253 ± 2.0) mm. All participants signed written informed consent prior to participating in the study.

(4) Plantar Pressure Testing

Regional plantar loading analysis provides a validated methodology for assessing footwear cushioning performance. This investigation employed the Pedar-X system to quantify in-shoe biomechanical parameters across midsole variants. The instrumented insoles incorporate 99 capacitive sensors with a thickness of 1.9 mm, operating at a 50 Hz sampling frequency within a 15–1200 kPa measurement range. An EU size 42/43 Pedar insole was selected for the experiment. The pressure measurement system divided the plantar foot into seven regions: hallux, toes 2–5, first metatarsal head (MTH 1), second metatarsal head (MTH 2), third–fifth metatarsal heads (MTH 3–5), midfoot, and hindfoot (Figure 2). Referring to relevant studies, participants were required to warm up and perform vertical jump-reach activities to familiarize themselves with the vertical jumping motion before starting pressure testing for each midsole.

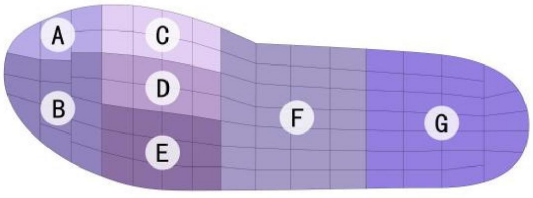

Figure 2. Instrumented plantar regions used for peak pressure and contact area analysis: (A) Hallux. (B) Toes 2–5. (C) First metatarsal head. (D)

	Second metatarsal head. (E) Third–fifth metatarsal heads. (F) Midfoot. (G) Hindfoot. Through plantar pressure measurement experiments, peak pressure in each plantar region, the maximum foot-shoe contact area, Vertical Impact Loading Rate (VILR), and CoP displacement were obtained. The VILR was quantified as the derivative of vertical ground reaction force between initial foot-ground contact and impact peak, expressed in N/ms. All 3D-printed midsoles maintained structural integrity through 100 consecutive jump tests without permanent deformation, demonstrating compressive durability and impact resistance. Written informed consent was acquired from all experimental participants prior to biomechanical assessments. Additionally, based on the CoP displacement trajectory during jump landing obtained from plantar pressure measurement experiments, the total mediolateral CoP deviation was derived using the calculation method of H.F. Leong, et al. First, the origin Xi was defined as the most posterior point of the CoP trajectory. Next, the mediolateral deviation was determined in relation to the x-axis, which is perpendicular to the longitudinal foot axis. The x coordinates (mediolateral locations of CoP) throughout the stance phase of the selected jump-landing steps were extracted. The total CoP mediolateral deviation was then calculated by summing the absolute differences between the x coordinates and the CoP path, i.e., $\|X2-X1\|+\|X3-X2\|+...+\|Xi-Xi-1\|$. (5) Jump-Landing Posture Data Collection Displacement data of jump-landing postures in the experiment were collected for subsequent finite element analysis. Mechanical characterization of 3D-printed TPU specimens was conducted using an Inspekt Table Blue 5KN universal testing system. Tensile and

compressive behaviors were evaluated following ASTM D638-14 and D395-03 standard test methods, respectively. Uniaxial testing yielded stress-strain data for hyperelastic material modeling.

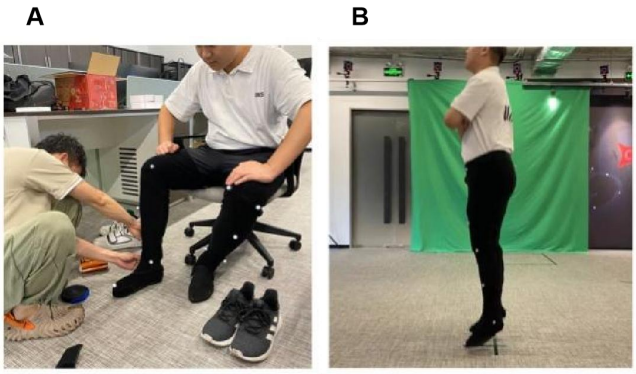

Figure 3. Kinematic data measurement: (A) Preparation for motion capture. (B) Kinematic data collection during the jumping process.

A digital foot model was developed from 3D scans of a male subject (height: 175 cm, shoe size: EU 42) acquired using an eFoot 350 medical scanner. To enhance anatomical fidelity, a bone model matching the foot dimensions was integrated into the soft tissue reconstruction. Footwear interaction dynamics were simulated during motion, with kinematic data captured at 300 Hz using a NOKOV Mars 9H optical system. As shown in Figure 3, reflective markers were positioned at key anatomical landmarks (heel, toe, medial/lateral malleoli, abdomen, and hip) to track the center of mass trajectory during jump-landing. This center of mass position was calculated as 40% of the abdomen-hip distance per W. Erdman's method.

III. Ethical Risk Prevention and Control & Protection of Subject Rights

This study strictly adheres to the ethical guidelines of the "Declaration of Helsinki," ensuring that subjects voluntarily sign an informed consent form based on a full understanding of the research

	purpose, procedures, potential risks, and benefits. Subjects are clearly informed of their right to withdraw unconditionally at any stage of the research without suffering any unfair treatment or loss. The experimental design employs standard movements assessed as low-risk, equipped with professional protective facilities. The entire research process is monitored by trained personnel, and emergency plans are formulated to fully guarantee the physical safety and mental health of the subjects. During the experiment, if a participant feels any pain, dizziness, or severe discomfort, the experiment will be stopped immediately. In the plantar pressure test experiment, all collected personal identity information and biomechanical data will be instantly anonymized and coded. Regarding the use of image data: to accurately analyze your movements, this study will use optical cameras to record your jumping process after attaching reflective markers. All images will be anonymized (e.g., faces will not be filmed), used solely for biomechanical analysis, and linked to your other data via coding. Without your additional explicit permission, these images will not be used for any public demonstration or promotion. Subjects have the right to know about their personal data; data is limited to use in this study and will be securely destroyed after the project ends according to the prescribed time limit. We will provide reasonable remuneration or compensation in accordance with ethical standards for the time and effort contributed by subjects participating in the research. The entire experimental process is subject to continuous supervision and review by the Ethics Committee.
Applicant's Commitment	I commit that the subjects in the project participate in the experiment with fully informed consent, without any pressure or deception, and that the experiment is premised on and starts from

	safeguarding the interests of the subjects. I will consciously abide by laws, administrative regulations, and relevant national provisions, not endangering human health or violating ethical morals. I will strictly standardize experimental procedures to protect the life safety and physical health of the subjects. I am ready to accept the supervision and inspection of the Academic Ethics and Scientific Technology Ethics Special Committee of Guangdong University of Technology at any time. If I violate regulations, I voluntarily accept punishment. Applicant Signature: Jifa Zhang Date: December 30, 2025
Review Opinion of Affiliated Unit	After preliminary review, the human experiment protocol of this project passes the ethical review and complies with national laws and regulations and ethical principles of human experiments. Head of the Unit: Xiaoyin Tang Applying Unit (Seal): Guangdong University of Technology, College of Art and Design (Signature) Date: December 30, 2025
Review Opinion of Academic Ethics and Scientific Technology Ethics Special Committee	Agree with the review opinion of the college. Academic Ethics and Scientific Technology Ethics Special Committee Chairman (Signature): Dingbang Lu Academic Ethics and Scientific Technology Ethics Special Committee Special Committee (Seal): Academic Committee of Guangdong University of Technology Date: December 30, 2025

(Note: This form should be printed double-sided)

Attached List:

Achievement Title	Augment Cushioning and Stability in Jump-Landing: Biomechanical Assessment of Auxetic Lattice Structures in Athletic Footwear Midsoles
Achievement Accepting Unit	Scientific Reports
Purpose, Methods, Expected Benefits, Potential Risks, General Procedure, and Calculation Basis of Human Experiment	**I. Purpose of the Human Experiment** To evaluate and compare the biomechanical performance of 3D-printed shoe midsoles with different internal geometries (specifically auxetic structures exhibiting a negative Poisson's ratio) under dynamic impact. By contrasting these with traditional polyurethane (PU) midsoles and non-auxetic lattice midsoles, the study aims to investigate the potential advantages of auxetic structures in shock absorption and motion stability. Specific research objectives include: (1) Investigation of Structural Effects: Under strictly controlled conditions of material volume, density, and overall dimensions, identify the influence of lattice geometry (primarily the internal angle) on midsole performance, focusing on the differences between 60° and 75° auxetic structures versus the 90° traditional structure. (2) Quantification of Biomechanical Performance: Through standardized subject wearing trials, quantify key biomechanical parameters of different midsoles when subjected to high-intensity impact (vertical jump landing). **II. Expected Benefits** This study is expected to provide core value for sports equipment innovation and related research through systematic biomechanical evaluation across multiple dimensions:

	(1) Product Design and Application: The study will provide direct theoretical basis and data support for developing a new generation of high-performance cushioned shoe midsoles. By comparing the biomechanical responses of auxetic and conventional structures, it aims to clarify the quantitative advantages of lattices with specific negative Poisson's ratios in dispersing impact forces, reducing vertical impact loading rates, and enhancing motion stability. This will guide the R&D of personalized footwear for high-impact sports (e.g., running, basketball) or special rehabilitation needs. (2) Scientific Research and Theoretical Validation: The research will empirically test the actual efficacy of auxetic structure theory under dynamic biomechanical loading environments. The precise material properties, individualized foot-shoe interaction models, and multi-parameter biomechanical data obtained will provide a high-quality foundational dataset for subsequent research in biomechanics, materials science, and ergonomics. Furthermore, the finite element model integrated with real kinematic data constitutes a reusable and expandable simulation platform, offering an efficient research tool for future studies on biomechanical mechanisms under different structures, materials, or movement patterns. (3) Methodology and Social Benefits: This study establishes an interdisciplinary research methodology integrating advanced manufacturing (3D printing), standardized human trials, and high-fidelity computer simulation. This paradigm not only enhances the efficiency and depth of sports equipment evaluation but also sets operational standards for similar human biomechanical research through rigorous ethical execution

	and protection of subject rights. Ultimately, the research outcomes are expected to translate into specific products and technical solutions that improve sports safety, optimize athletic performance, or assist rehabilitation engineering, serving broader public health needs. **III. Potential Risks** Potential risks in this experiment mainly include: 1) Risk of Sports Injury: Participants performing standardized vertical jumps may face possibilities of ankle sprains, muscle strains, or falls; 2) Equipment-related Risks: The insole pressure measurement system may cause transient discomfort, although ultra-thin designs have been adopted. All risks have been minimized through professional protective measures, adequate warm-ups, and full-process monitoring. **IV. General Procedure of the Human Experiment** The experiment recruited 20 healthy male subjects meeting strict criteria, all uniformly wearing EU size 42 footwear. The Pedar-X in-shoe pressure measurement system was used to collect biomechanical data during jump landings. The entire process was conducted in a controlled laboratory setting, lasting approximately 60–90 minutes per subject to ensure standardization and data comparability. Specific steps are as follows: (1) Publicly recruit 20 healthy male subjects meeting strict inclusion criteria. Before the formal experiment, researchers will explain the purpose, procedure, potential risks, and rights to each subject in detail. Written informed consent will be obtained after they fully understand the information. (2) Uniform EU size 42 experimental shoes will be used. Researchers will equip each subject with Pedar-X insoles matching

	their shoe size and guide them to insert the insoles correctly into the experimental shoes, ensuring full contact between the sensors and the sole of the foot. (3) Before formal testing, subjects will perform standardized warm-up activities under researcher guidance, followed by several practice trials of vertical jump-landing actions. This ensures familiarity with testing requirements and standardizes movements (take-off height, landing posture, etc.) to minimize intra-subject error. (4) Each subject will sequentially wear four different experimental midsoles (A60, A75, N90, and PU control) to complete the tests. For each midsole, the subject must perform several valid vertical jump-landing actions. During each action: The Pedar-X system will continuously collect pressure distribution at the interface between the foot and the midsole inside the shoe at a frequency of 50 Hz, recording peak pressure, contact area, center of pressure trajectory, etc., for each region in real time. Researchers will monitor the entire process to ensure safety and compliance and record the number of valid trials. (5) Immediately after a single test session, data integrity and quality will be checked. All biomechanical data will be anonymized and coded, decoupled from subjects' personal information. (6) After all tests are completed, it will be confirmed that subjects have no discomfort. The acquired anonymized data will be used for subsequent statistical analysis and compared with synchronous material mechanics test results and finite element simulation results in a multi-modal manner to comprehensively evaluate the biomechanical performance of different midsoles. **V. Required Number of Subjects and Calculation Basis**

	The study requires a total of 20 healthy male subjects. The basis for this sample size calculation primarily relies on common sample size ranges in biomechanical research and statistical power considerations. Under the premise of strictly executing homogenization screening criteria (controlling shoe size and foot health status), a sample of 20 is sufficient to reflect the basic characteristics of the target population while ensuring data stability and analyzability. Combined with finite element simulation validation, this approach can, to some extent, compensate for the limitations of a small sample size and enhance the reliability of the research conclusions.
Signed Informed Consent with Subjects	Yes. (The informed consent form is attached.)
Applicant's Commitment	I hereby certify that the information provided above is true and reliable, and I commit to consciously complying with national laws and regulations as well as the ethical principles governing human experimentation. Applicant Signature: Jifa Zhang Date: December 30, 2025