Electromyograph (EMG) Analysis of personalised 3D-Printed Auxetic and Conventional Mesh Insoles for Pes Planus Individual: A Pilot Study

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Electromyograph (EMG) Analysis of personalised 3D-Printed Auxetic and Conventional Mesh Insoles for Pes Planus Individual: A Pilot Study

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Abstract: *This study investigates the customization of 3D-printed orthotic insoles for individuals aged 18–25 with flat feet (pes planus). Pes planus is marked by a reduced medial arch, causing discomfort and biomechanical imbalances. Off-the-shelf insoles offer limited support due to lack of customization. This project employs 3D foot scanning and auxetic mesh structures to fabricate personalized insoles using SolidWorks and 3D printing. The study examines the effects of auxetic and non auxetic on performance and support through electromyography (EMG) testing. Expected outcomes include improved muscle activity, reduced muscle fatigue, and enhanced overall foot biomechanics. The goal is to develop an affordable, efficient solution to improve quality of life for those affected by flat feet.*

Keywords: Auxetic structure; pes planus; insole design; 3D printing; electromyography

1. INTRODUCTION

Pes planus, commonly known as flat feet, is defined by a diminished medial longitudinal arch that can lead to an abnormal gait, postural instability, and musculoskeletal discomfort. This condition is generally divided into two types: a rigid form which is usually congenital and may necessitate surgical intervention and a flexible form [1]. Improper weight distribution during activities such as walking or running often results in pain and fatigue among affected individuals [2].

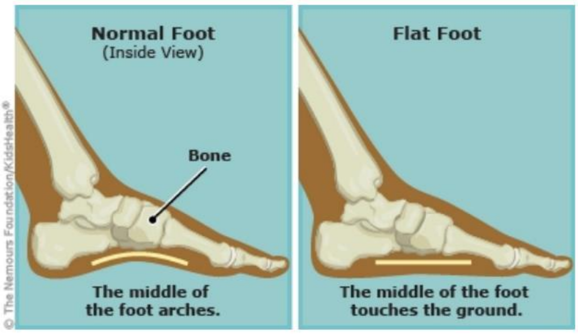

Fig. 1.1 Anatomical Differences Between Normal feet and Flat feet

Fig. 1 illustrates the anatomical differences between normal and flatfeet. In normal feet, the middle of the feet remains elevated above the ground due to the presence of a well-defined longitudinal arch. This arch plays a crucial role in uniformly distributing forces throughout the feet while walking or running, providing stability and acting as a natural shock absorber [7].

Mass-produced, off-the-shelf insoles are typically standardized based on general foot dimensions, offering limited corrective support. In contrast, custom orthotic insoles, developed using detailed 3D foot scans, provide a closer match to individual foot anatomy, thereby enhancing stability, comfort, and pressure relief [3,4].
Advances in 3D printing technology have made it possible to incorporate auxetic structures, materials exhibiting a negative Poisson's ratio that expand laterally under tension and contract under compression into insole design. High-precision 3D reconstruction is crucial for accurate inspection and functional evaluation of anatomical structures [8]. These innovative lattice configurations improve shock absorption, conformability, and overall biomechanical performance [5,6].
This study focuses on evaluating the performance of 3D-printed insoles with a 60° auxetic mesh structure compared to a conventional non-auxetic design. Using SolidWorks for insoles designing and electromyography (EMG) for analyzing muscle activity, the research aims to assess which configuration provides better biomechanical support for individuals with pes planus.

2. RESEARCH METHOD

This study was carried out through several key stages: subject recruitment, foot scanning, insole design, fabrication, and performance evaluation through simulation and electromyography (EMG). Each phase was completed to ensure the accurate development and assessment of 3D-printed insoles for individuals with pes planus.

2.1 Subject Selection

Two female and one male volunteers aged between 18 and 25 years, previously diagnosed with pes planus, were recruited for this study. The inclusion criteria involved non-athletic individuals without recent foot injuries, surgeries, or previous use of custom insoles. Volunteers with other foot deformities, poor general health, or who were pregnant were excluded. All participants were informed about the experimental procedures, benefits, and potential risks, and written consent was obtained.

Fig. 2.1 Pes planus of young adult from side view

Fig. 2.2 Pes planus of young adult from back view

Fig. 2.1 and 2.2 show real-life images of the first volunteer's feet. The absence of curvature causes the entire foot to appear more horizontal and closer to the ground.

2.2 Insole Design

The insole designs were developed using SolidWorks based on standard foot dimensions and prior design parameters for flat-footed individuals. Two types of internal mesh structures were created: a re-entrant auxetic pattern with a 60° internal angle, and a conventional non-auxetic pattern. These geometries were selected to compare how structural differences influence muscle performance during weight-bearing activities.

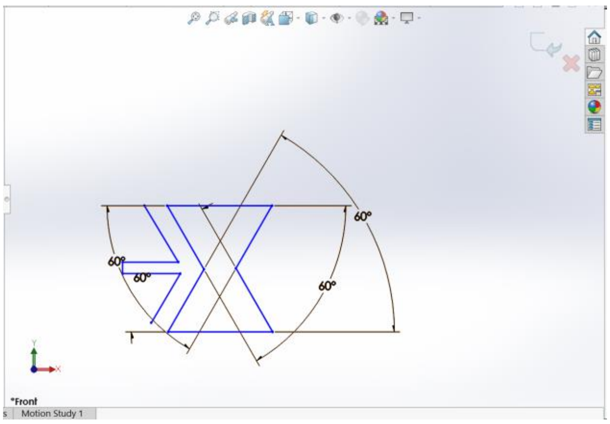

Fig. 2.3 Initial sketch of auxetic structure with 60° internal angle

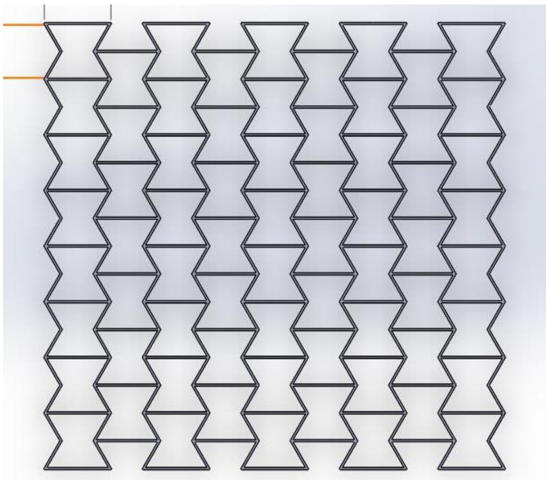

Fig. 2.4 Duplicated auxetic structure with 60° internal angle

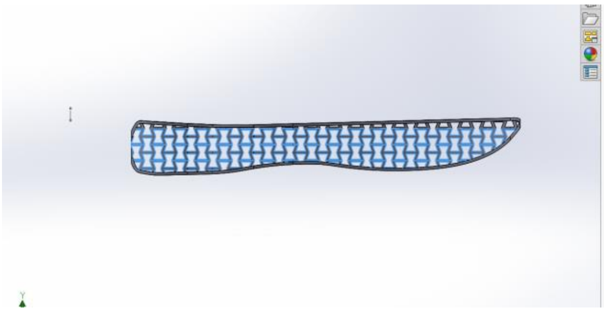

Fig. 2.5 Auxetic structure integrated in insole

Fig. 2.3 illustrates the initial sketch of the auxetic structure featuring an internal angle of 60°. In Fig. 2.4, the design is duplicated to form a continuous pattern while maintaining the same internal angle. Fig. 2.5 presents the integration of the auxetic structure into the insole design. The mesh structure was integrated horizontally along the plantar surface of the insole to maximize surface contact and conformability.

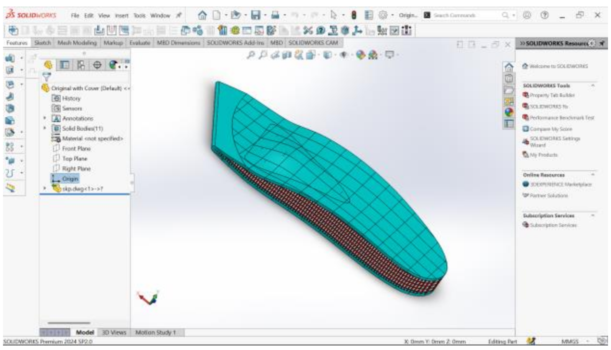

Fig. 2.6 Final insoles design

Fig. 2.6 displays the final insole design, featuring an elevated medial arch. The auxetic design was expected to allow for lateral expansion under pressure, offering improved adaptability to the foot’s arch and more uniform pressure distribution [7]. In both models, the lattice extended from the heel to the forefoot region, targeting areas typically affected by excess pressure in individuals with pes planus.

2.3 3D Foot Scanning

Each volunteer's foot morphology was captured using a Sense Pro handheld 3D scanner (see Fig. 2.7). The scanning process was conducted in a controlled, well-lit environment to ensure optimal image clarity and accuracy. Volunteers were seated comfortably (see Fig. 2.8), and their feet were cleaned with antibacterial wipes before scanning to ensure hygiene and reduce skin reflectivity.

Fig. 2.7 Sense Pro handheld 3D scanner

Fig. 2.8 Positioning of the volunteer's feet

The scanner was moved steadily around each foot to capture anatomical details from all angles, particularly the medial arch, heel, and forefoot areas (see Fig. 2.9) are was taken to maintain a consistent distance between the scanner and the foot (approximately 20-30 cm) to reduce distortion.

Fig. 2.9. Scanning the feet

After scanning, the data were processed to clean up any noise, fill gaps, and refine the mesh structure. The finalized 3D models were exported in STL format and served as the foundation for designing custom-fitted insoles in the subsequent design phase.

Fig. 2.10 3D foot model result

After foot scanning was carried out, the resulting 3D foot models (see Fig. 2.10) were imported and aligned with the pre-designed insoles to assess fit (see Fig. 2.11). This step ensured that the geometrical dimensions of the insole, particularly arch height, heel width, and forefoot curvature closely matched the individual anatomy of each volunteer. Any minor adjustments required to improve compatibility were made to the insole model before proceeding to fabrication.

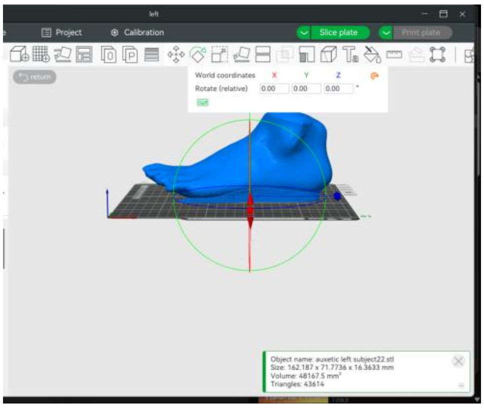

Fig. 2.11 Aligning process of the insoles and feet

2.4 Insole Fabrication

After completing the foot design aligning phase, the digital models were prepared for 3D printing using thermoplastic polyurethane (TPU) filament (see Fig. 2.13). TPU was chosen for its flexibility, durability, and skin-friendly properties, making it well-suited for insole applications. The designs were sliced using Bambu 3D printing software, and printing parameters were optimized to balance structural integrity with softness (see Fig. 2.12).

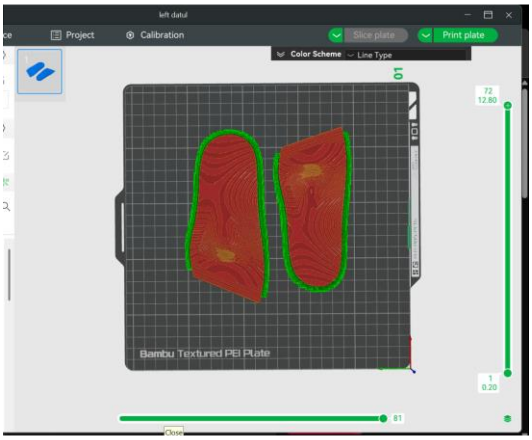

Fig. 2.12 Bambu 3D printing software

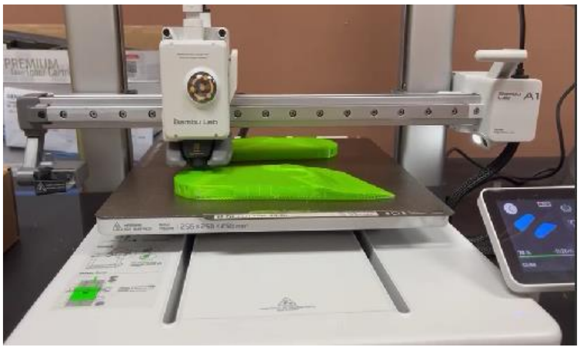

Fig. 2.13 3D printing process

Once printed, the insoles were carefully removed from the print bed and trimmed to eliminate any support material or surface irregularities. Fig. 2.14 shows the complete printed auxetic insoles for three volunteers. Post-processing also involved checking for dimensional accuracy and consistency with the scanned foot models. Each printed insole was matched to its corresponding volunteer's foot morphology to confirm compatibility before use in mechanical testing and EMG evaluation.

Fig. 2.14 Printed insoles

2.5 Electromyography (EMG) Testing

To evaluate muscle activation and fatigue associated with the use of different insole types, electromyography (EMG) testing was performed using a Plux biosignals EMG device (see Fig. 1.15).

Fig. 2.15 4 channels Plux biosignals EMG

Fig. 2.16 Electrode placement

Fig. 17 shows the surface electrodes were placed on the gastrocnemius muscle of each participant's dominant leg to monitor muscle activity during running. Prior to electrode placement, the skin was cleaned thoroughly with alcohol wipes to reduce surface impedance and ensure signal clarity.

Fig. 2.17 Printed insoles

Fig. 2.18 3.5m/s pace

Fig. 2.17 shows the volunteer underwent a short warm-up session consisting of a 1.5 km walk on a treadmill to normalize their gait pattern. After the warm-up, participants were asked to run on the treadmill at a consistent speed of 3.5 m/s (see Fig 2.18.) for a duration of three minutes while wearing each type of insole first the auxetic insole (60°) and then the non-auxetic insole [9]. Between each trial, a rest period of 10 to 15 minutes was provided to prevent carryover fatigue and ensure reliable EMG measurements.

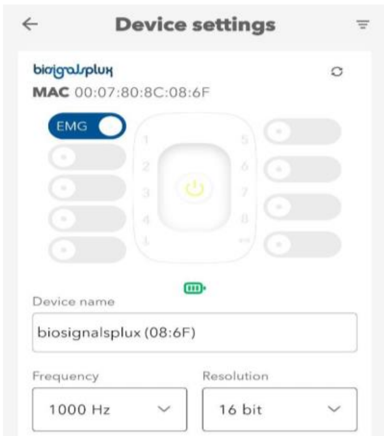

Fig. 2.19 4 channels Plux biosignals EMG

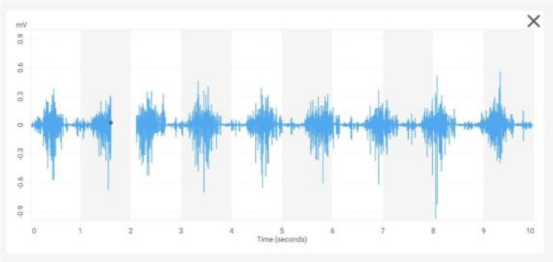

Fig. 2.20 Real time signal (auxetic insoles)

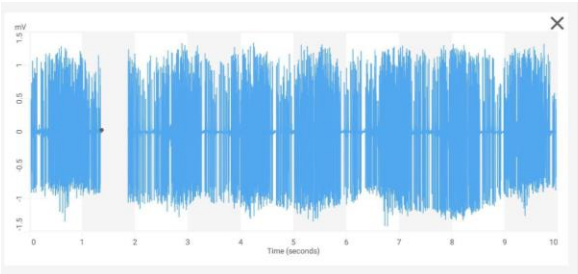

Fig. 2.21 Real time signal (non auxetic insoles)

Fig. 2.19 shows the device configuration upon successful connection to the sensor. Fig. 2.20 and 2.21 illustrate a comparison of the real-time muscle activity signals recorded while subjects performed physical activities using both auxetic and non-auxetic insoles.

The EMG signals were collected and processed to extract key indicators such as Root Mean Square (RMS) and Median Frequency (MF). RMS was used to quantify muscle activation intensity, while MF was analyzed to assess muscle fatigue. The data obtained for each insole condition were compared to evaluate differences in muscle performance, thereby providing insight into the biomechanical impact of each insole structure on lower limb activity in individuals with pes planus [10].

3. RESULTS AND DISCUSSION

Electromyography (EMG) analysis was conducted to evaluate and compare muscle activity and fatigue patterns between the auxetic insole (60°) and the non-auxetic insole.

3.1 MATLAB Visualization and Analysis

To evaluate the muscular activity during the use of 3D printed insoles (auxetic vs. non-auxetic), surface electromyography (sEMG) data was analyzed through a standard signal processing pipeline in MATLAB. The steps included data loading, filtering, rectification, smoothing, and extraction of time and frequency-domain features.

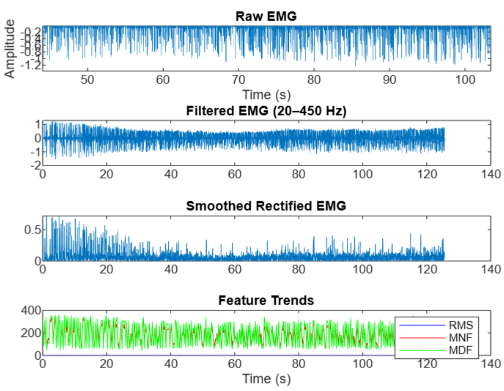

Fig 3.1 Auxetic Signal 1st Volunteer

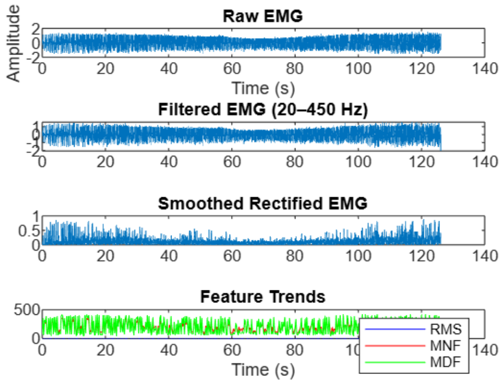

Fig 3.2 Non Auxetic Signal 1st Volunteer

Based on Figure Auxetic Signal 1st Volunteer, the RMS curve for the auxetic insole shows a stable and moderate amplitude throughout the 3-minute run, indicating consistent muscle activation and reduced fatigue. In comparison, Figure Non-Auxetic Signal 1st Volunteer displays higher and more erratic RMS peaks, reflecting greater muscle strain and less consistent engagement [10].

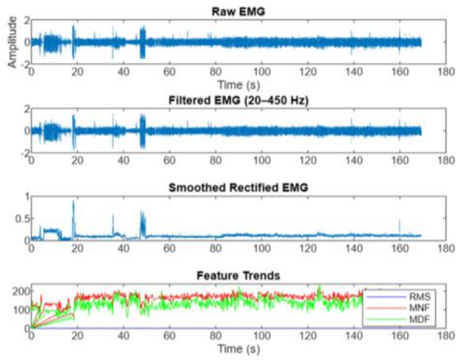

Fig 3.2 Auxetic Signal 2nd Volunteer

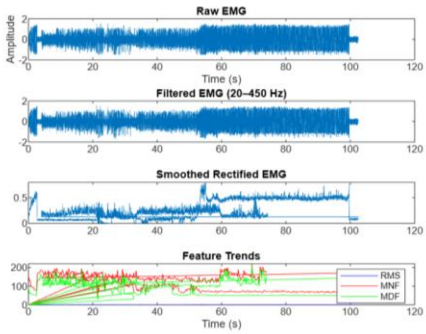

Fig 3.4 Non Auxetic Signal 2nd Volunteer

Similarly, Figure Auxetic Signal 2nd Volunteer and Figure Auxetic Signal 3rd Volunteer exhibit smooth and steady MNF and MDF trends, showing delayed fatigue and efficient muscle firing. In contrast, Figures Non-Auxetic Signal 2nd and 3rd Volunteers show frequent dips and fluctuations in both MNF and MDF, suggesting early onset of fatigue and unstable muscle activity.

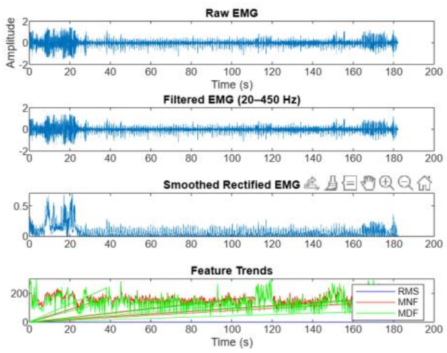

Fig 3.5 Auxetic Signal 3rd Volunteer

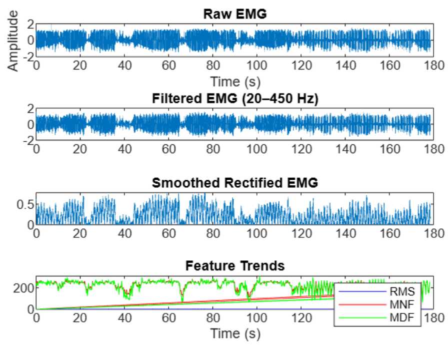

Fig 3.6 Non Auxetic Signal 3rd Volunteer

3.2 Quantitative Summary

The comparison between auxetic and non-auxetic insoles using EMG analysis reveals notable distinctions in muscle performance across multiple domains: amplitude-based intensity (RMS), frequency-based fatigue indicators (MNF and MDF), and signal variability (standard deviation). These findings were substantiated through both visual interpretation of EMG signal plots and detailed numerical summaries presented in Tables 3.1 through 3.3.

Table 3.1. EMG Feature Summary for 1st Volunteer

Feature	Auxetic	Non-Auxetic
Mean	0.00198	0.0015
Median	0.00418	0.0058
Standard Deviation	0.0510	0.2670
RMS	0.1510	0.2670
Minimum Amplitude	-1.4871	-1.4870
Maximum Amplitude	1.4779	1.4880
Amplitude Range	2.9650	2.9751
Mean Frequency	216 Hz	258.07 Hz
Median Frequency	227 Hz	291.74 Hz

Table 3.2 EMG Feature Summary for 2nd Volunteer

Feature	Auxetic	Non-Auxetic
Mean	0.00198	0.0015
Median	0.00418	0.0058
Standard Deviation	0.1664	0.3854
RMS	0.1664	0.3597
Minimum Amplitude	-1.4874	-1.4871
Maximum Amplitude	1.4880	1.4880
Amplitude Range	2.9754	2.9752
Mean Frequency	230.06 Hz	246.53 Hz
Median Frequency	215.73 Hz	261.72 Hz

Table 3.3 EMG Feature Summary for 3rd Volunteer

Feature	Auxetic	Non-Auxetic
Mean	0.0022	0.0015
Median	0.0041	0.0036
Standard Deviation	0.1425	0.3596
RMS	0.1426	0.3597
Minimum Amplitude	-1.4871	-1.4871
Maximum Amplitude	1.4779	1.4880
Amplitude Range	2.9650	2.9751
Mean Frequency	190.86 Hz	260.30 Hz
Median Frequency	163.09 Hz	254.88 Hz

Across all subjects, the RMS values, which indicate the overall intensity of muscle activation during the activity, were consistently lower when auxetic insoles were used. For instance, the 1st volunteer recorded an RMS of 0.1510 with the auxetic insole and 0.2670 with the non-auxetic. Similar reductions were observed for 2nd volunteer (0.1664 vs. 0.3597) and 3rd volunteer (0.1426 vs. 0.3597). A lower RMS implies that the muscle required less energy to perform the same task, indicating reduced muscle effort and greater biomechanical efficiency. This supports findings by Bednarczyk [3], who demonstrated that custom-designed insoles contribute to improved pressure distribution and muscle load optimization.

The Mean Frequency (MNF) and Median Frequency (MDF), which are derived from the spectral analysis of the EMG signal, serve as reliable indicators of muscle fatigue. As muscle fatigue develops, the conduction velocity of motor units slows down, resulting in a downward shift of the frequency spectrum. Thus, a reduction in MF or MDF over time is typically interpreted as the onset of fatigue [9].

In the present study, while some non-auxetic conditions showed higher MNF and MDF values (e.g., 2nd volunteer: MNF = 246.53 Hz vs. 230.06 Hz; MDF = 261.72 Hz vs. 215.73 Hz), these values must be interpreted in conjunction with RMS and standard deviation. The combination of high RMS and high signal variability under the non-auxetic condition suggests that these elevated frequencies may not indicate greater efficiency but instead reflect increased muscular demand or overuse due to insufficient insole support. As highlighted by Shakhih [10], evaluating fatigue requires observing multiple EMG features together, particularly

frequency shifts in tandem with amplitude variability.
In parallel, standard deviation values were substantially lower under the auxetic condition for all three subjects (e.g., 2nd volunteer: 0.1664 auxetic vs. 0.3854 non-auxetic). Standard deviation reflects the variability of muscle signal amplitude. A lower value suggests more consistent and stable muscle contractions, whereas a higher value in the non-auxetic condition points to erratic or compensatory activation, likely due to less effective mechanical support [10]. This consistency is critical in reducing the likelihood of premature fatigue and muscular overcompensation during repetitive movement.

In summary, the numerical data collectively demonstrate that auxetic insoles provide superior biomechanical conditions, evidenced by lower muscle effort (RMS), greater signal stability (low SD), and more controlled activation (mean/median amplitude proximity). Despite occasional higher frequency values in the non-auxetic condition, the associated signal instability and amplitude spikes suggest less sustainable performance and earlier fatigue, aligning with prior literature on EMG fatigue analysis in gait and orthotic studies [9,10].

Auxetic insoles leverage a negative Poisson's ratio, meaning their re-entrant cells spread laterally when compressed and thereby cradle the medial arch instead of collapsing; by locally adjusting cell angle, size or infill density, engineers can create a heel zone that stays compliant for impact cushioning while the mid-foot region is deliberately stiffened to guide smoother load transfer, and the lattice's ability to store and return elastic energy adds extra damping, which helps explain the lower EMG muscle-effort and delayed-fatigue patterns seen in pilot studies [11,12,13].

While the findings of this pilot study suggest promising biomechanical benefits of auxetic insoles, several limitations must be acknowledged. Only three volunteers participated in the EMG analysis, which restricts the generalizability of the results. This small sample size may not adequately represent the broader population of individuals with pes planus, particularly across diverse age groups, activity levels, or severity grades. Future studies should involve larger and more varied cohorts to enhance statistical power and confirm the consistency of observed muscle activation and fatigue patterns. Additionally, exploring alternative auxetic designs, such as varying cell geometry or angle, could offer further insights into optimising insole performance for different user needs.

4. CONCLUSION

This study demonstrated that 3D printed insoles featuring a 60° auxetic mesh design fabricated from TPU and tailored via 3D foot scanning offer clear biomechanical advantages for individuals with pes planus compared to conventional non auxetic insoles. Electromyography (EMG) data revealed that the auxetic insoles produced more stable muscle activation, reduced overall muscle effort (lower RMS), and delayed fatigue (higher mean and median frequency), whereas non auxetic insoles elicited higher activation intensity and earlier fatigue signs. By combining additive manufacturing with an auxetic lattice, this personalized cost effective approach improves foot support, comfort, and biomechanical performance, warranting validation through larger cohorts and longer term wear studies.

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