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Posted Date: 26 February 2026

doi: 10.20944/preprints202602.1407.v1

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Article

Investigating the Performance Characteristics of Auxetic Foams in Neuropathy Treatment Applications

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Abstract

Research into auxetic foams and their impact on ground reaction forces (GRFs) across diverse neuropathic etiologies is limited. Auxetic foams—closed-cell materials with a negative Poisson's ratio—conform to irregular foot structures, offering significant rehabilitative potential to mitigate symptoms by optimizing GRF reduction and enhancing gait. Currently, there is a lack of versatile orthoses capable of addressing the heterogeneous subtypes of foot neuropathy. Conducted in collaboration with the National Aeronautics Space Administration/Marshall Space Flight Center (NASA/MSFC), this feasibility study evaluates the efficacy of auxetic foam insoles in reducing vertical GRFs and improving gait across various neuropathic conditions, comparing performance against standard over-the-counter (OTC) insoles. Six participants (five with varying neuropathic etiologies and one healthy control) performed walking trials across force plates (NUL225, NEULOG) under three conditions: barefoot (with socks), OTC insoles, and fabricated auxetic foam insoles. A 3 × 5 Kruskal-Wallis test analyzed the impact of insole type and neuropathic condition on vertical GRFs ($\alpha=0.05$). Results indicated a significant interaction between insole type and neuropathy. Auxetic foam insoles effectively reduced GRFs in participants with diabetic, neuropathic arthritis, and personal injury-related neuropathy. Qualitative assessments further demonstrated that auxetic foam significantly improved coordination and gait compared to OTC alternatives.

Keywords: neuropathy; ground reaction forces; gait; auxetic foams; insoles; orthotics; rehabilitation; health systems engineering

1. Introduction

Peripheral neuropathy encompasses disorders of the nerves outside the brain and spinal cord [1]. Affecting over 20 million people, this condition arises from metabolic, autoimmune, and hereditary factors, as well as trauma, infection, or radiation [1-4]. Nerve damage often results in impaired balance and coordination, which manifests as increased Ground Reaction Forces (GRFs) during locomotion [1-4].

GRFs are critical metrics in orthotic design, categorized into vertical, mediolateral, and anterior-posterior components. Vertical GRF is the primary focus for clinicians as it represents the largest force component during gait and is essential for musculoskeletal injury analysis, gait abnormality detection, and the evaluation of prosthetic and orthotic interventions [5-18].

Current orthotic designs primarily target diabetes-related neuropathy, the most prevalent subtype [19-24]. Consequently, existing rehabilitative orthoses often overlook other etiologies (e.g., oncology or trauma-related neuropathy) and fail to utilize novel materials that might better mitigate balance and coordination deficits. A comprehensive understanding of specific pathologies and foot types is necessary to inform effective rehabilitative strategies [25-26]. Given the complexity of neuropathy, management must include a detailed evaluation of etiology-specific characteristics, including GRFs [26].

Orthotics alleviate neuropathic pain by providing cushioning and reducing pressure points [27-29]. While custom-made orthotics are generally preferred [29-31], auxetic foams offer a novel alternative. Characterized by a negative Poisson's ratio—meaning they expand when stretched and contract when compressed [31] (Figure 1) —these materials provide superior shape conformity, energy absorption, and indentation resistance [32-39]. These unique properties suggest that auxetic foams may be more effective than traditional materials at reducing GRFs across heterogeneous neuropathic subtypes.

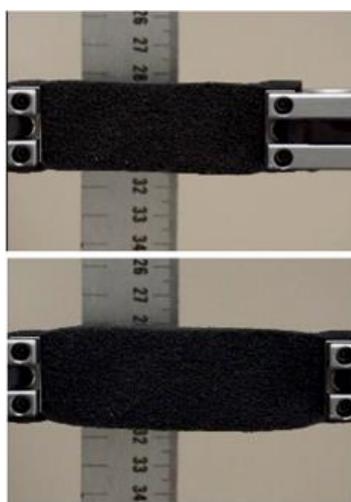


Figure 1. Auxetic foam expands in the transverse direction when stretched. The top panel shows the material in its original state, while the bottom panel illustrates the lateral expansion (widening) during applied tension, characteristic of a negative Poisson's ratio.

2. Materials and Methods

Participants

Six participants were recruited from NASA (Table 1). The cohort included five individuals with neuropathy attributed to diabetes (Subjects A & C), arthritis (Subject B), cancer (Subject D), and personal injury (Subject F), plus one healthy control (Subject E). Subject F utilized leg braces for additional stability. Inclusion criteria mandated a minimum age of 40 years to reflect the higher epidemiological prevalence of peripheral neuropathy in older populations. With the exception of the healthy control, all participants were required to have a confirmed diagnosis of neuropathy. All participants provided informed consent as approved by NASA's Institutional Review Board.

Table 1. Qualitative Data Analysis of Comfort and Gait Improvement with Auxetic Foam Technology

Subject	Gender	Weight	Neuropathy Cause / Attribute	Shoe Size	Shoes & Aids Worn at Site (Current)	Shoe Type for Auxetic Insole	Insole Comfort Level (vs. Current)	Gait Improvement (vs. Current)

A	M	205 lbs	Diabetes	10W	Timberlands (Dr. Scholl's)	Eduropro Comfort Gel (Black)	More comfortable	Walking is better
B	F	175 lbs	Cancer	9.5	New Balances (Memory Foam)	Athletic Works (White)	More comfortable	Walking is better
C	M	260 lbs	Diabetes	11	Slip-on wafers (Foam/Leather)	Athletic Works (Black)	About the same	About the same
D	F	155 lbs	Arthritis / Cancer	6.5	Sketchers (No special insole)	Athletic Works (Gray)	About the same	About the same
E	F	158 lbs	Control (No neuropathy)	6.5W	Sketchers (No special insole)	Athletic Works (Gray)	More comfortable	About the same
F	F	184 lbs	Personal Injury (Car accident)	10	Adidas (Dr. Scholl's) + AFO Braces	Athletic Works (Gray)	More comfortable	Walking is better

¹ This table presents qualitative feedback from subjects using auxetic insoles. Data collected includes subjective comfort levels and perceived gait improvement compared to the subjects' current footwear and aids.

Auxetic Foam and Insole Fabrication

The auxetic material was manufactured at FAMU-FSU via tri-axial compression of conventional polyurethane (PU) foam under elevated temperatures. This process induces buckling of the reticular cell ribs to create a re-entrant structure, which is then fixed into place [38-39]. The material formulation involved reactive foaming and phase separation of urethane, alcohol, and water (Figure 1b).

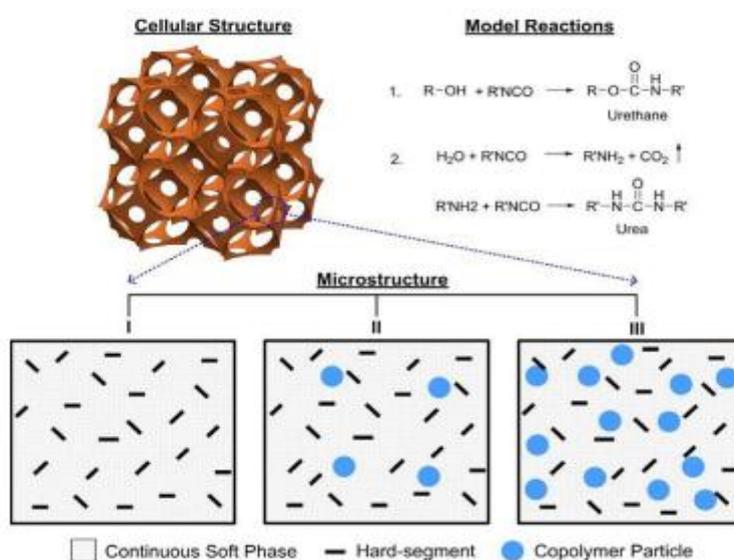


Figure 1. b. Illustration of typical polyurethane foaming reaction and phase-separated morphology.

To ensure proper fit, insoles were extracted from standard OTC brands (Eduropro, Comfort Gel, and Athletic Works) to serve as templates. These templates were traced onto the auxetic foam and cut to size, ensuring compatibility with the participants' existing footwear (sizes 6–13) (Figure 2).



Figure 2. left: CAD rendering of auxetic foam insole; right: a photograph of the auxetic foam insole.

Procedures

Baseline data, including age, weight, stride length, and shoe size, were recorded upon arrival (Table 1). Participants performed six walking trials at a self-selected pace across four force plates (Figure 3). Each trial consisted of walking four steps, turning, and returning to the starting position to ensure data collection for both the left and right feet. Testing was conducted under three conditions:

1. Barefoot (with socks).
2. OTC Insoles (non-auxetic).
3. Auxetic Foam Insoles.

Subject F performed additional trials with and without leg braces to isolate the impact of the auxetic material on their specific orthotic requirements. In each cycle, the participants' peak vertical GRFs were evaluated (Tables A 2–5), and their gait cycles were simultaneously observed using motion capture (MARVUE Video Camera Camcorder 2D device). Figure 3(b) illustrates a participant in the barefoot condition. Data from the fourth force plate were excluded from the final analysis due to inconsistent foot strikes; consequently, peak vertical GRFs from the remaining three plates were utilized.

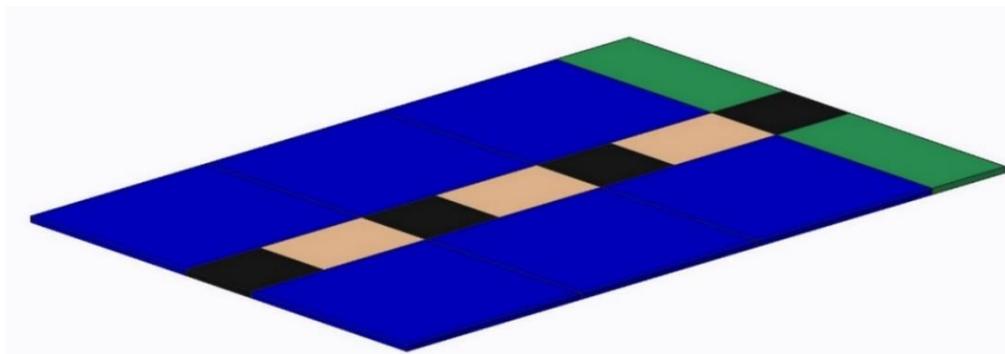


Figure 3. a. Schematic of Neuropathic and Auxetic foam insole test set-up.

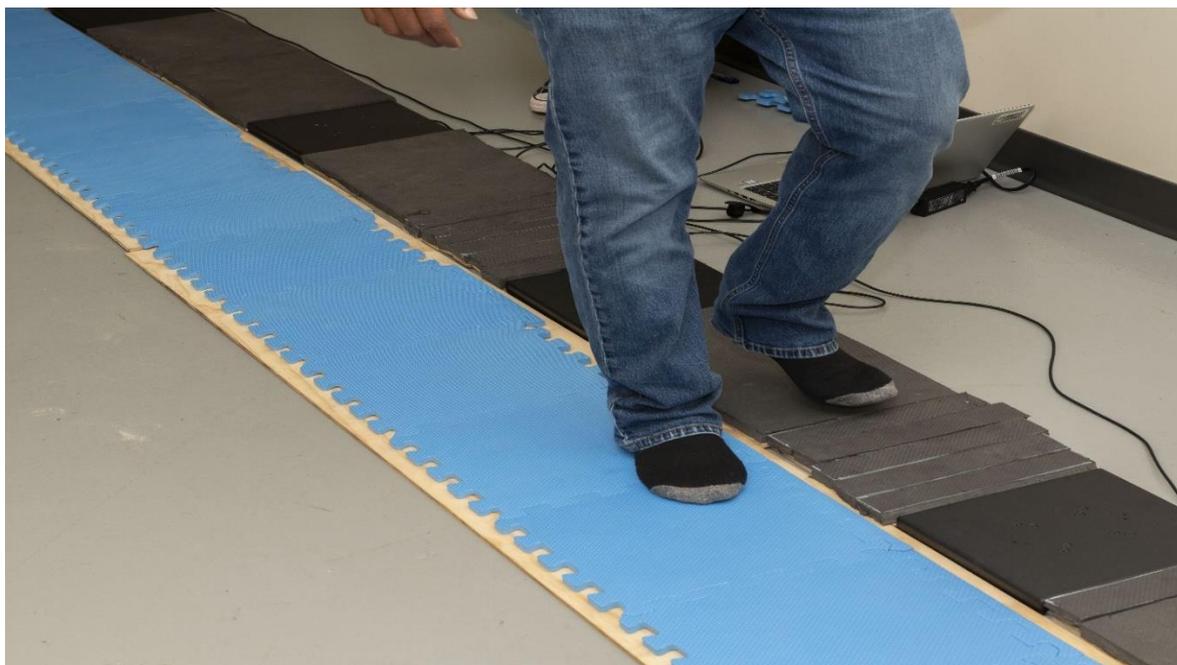


Figure 3. b. Subject walking and representative measurement of GRF in the barefoot (with socks) condition.

Measures and Analysis

Peak vertical GRFs and qualitative comfort assessments were compared between auxetic foam and OTC insoles. Due to the small sample size, normality was not assumed; therefore, this feasibility study utilized 3×5 (insole \times neuropathy subtype) Kruskal-Wallis tests. To account for the two subjects with diabetic neuropathy (A and C) and the use of leg braces by Subject F, four separate statistical iterations were performed (Tables A 6–9). These groupings allowed for a granular analysis of how auxetic material impacts GRFs across specific neuropathic subtypes. The independent variables were insole condition and neuropathic subtype, while peak vertical GRF served as the dependent variable. Data were numerically coded for group identification. The alpha level was set at $p < 0.05$, with a post-hoc Dunn's test applied to identify specific pairwise differences. Additionally, mean vertical GRFs were calculated per condition to quantify the percentage increase or decrease associated with the auxetic material.

3. Results

Statistically significant differences in vertical GRFs were observed across neuropathic subtypes and insole conditions ($p = 0.0001$; Tables A 6–9), confirming that both the etiology and the orthotic material significantly influence force distribution. An interaction effect between insole type and neuropathy was also identified. Specifically, auxetic foam reduced vertical GRFs in Subject A (diabetes), Subject D (arthritis), and Subject F (injury, without braces) compared to OTC insoles (Figure 4). Conversely, slight increases in GRFs were noted in Subjects B (cancer), C (diabetes), E (control), and F (injury, with braces) (Figure 5). These increases were attributed to external factors: swift walking cadences in Subjects E and C, the absence of assistive walking sticks for Subject B, and the mechanical influence of leg braces for Subject F. Despite varied GRF data, motion capture confirmed that all participants exhibited improved gait cycles when using the auxetic material.

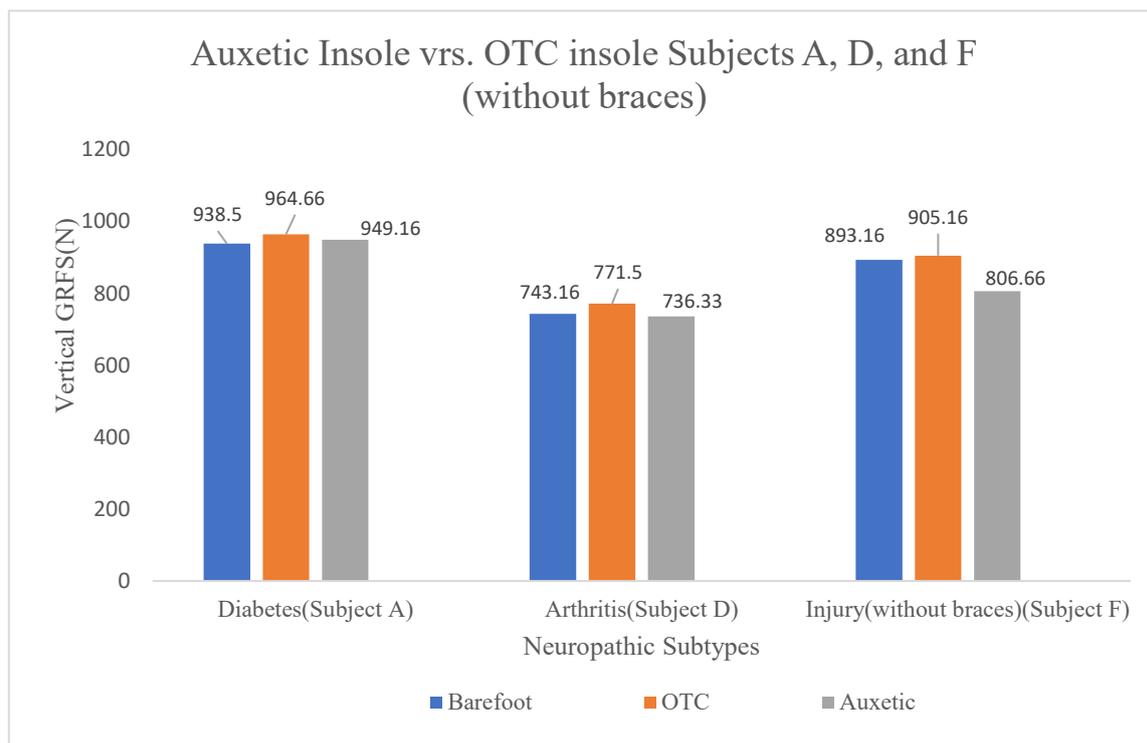


Figure 4. Subject-specific mean vertical ground reaction forces (N) during ambulation under three insole conditions (Barefoot, OTC, and Auxetic). The data indicate that the use of the Auxetic foam material resulted in lower vertical GRFs across participants with diabetes (A), arthritis (D), and injury-related neuropathy (without braces) (F).

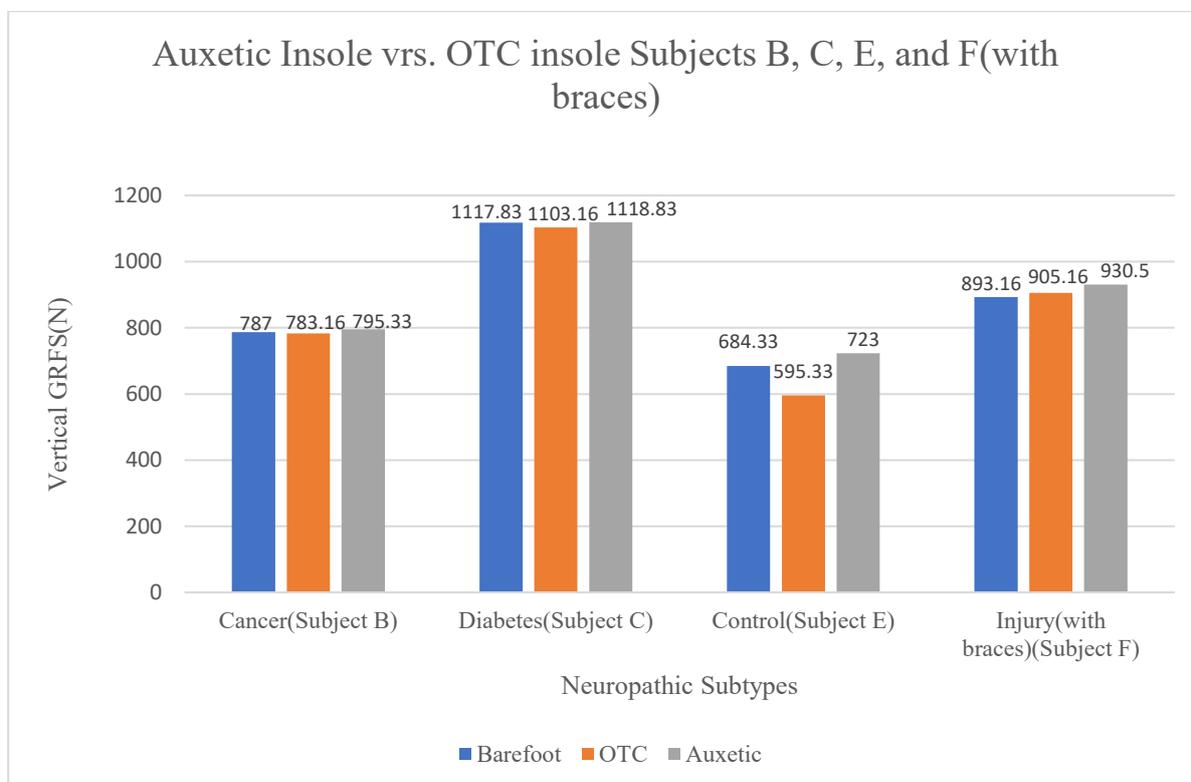


Figure 5. Subject-specific mean vertical ground reaction forces (N) during ambulation under three insole conditions (Barefoot, OTC, and Auxetic). The data indicate a general increase in vertical GRFs with the use of the Auxetic material across participants with cancer (B), diabetes (C), a healthy control (E), and injury-related neuropathy (brace condition) (F), which may be attributed to external factors.

4. Discussion

This study assessed the efficacy of auxetic foams—multi-phase cellular materials with a negative Poisson's ratio—in attenuating vertical GRFs compared to standard OTC insoles. This research challenges traditional orthotic design paradigms by applying systems engineering principles to address diverse neuropathic subtypes beyond diabetes. A robust engineering system must account for the synergy between its subsystems; here, the pathological variables of neuropathy and the mechanical properties of rehabilitative orthoses are treated as inseparable components of the patient's ambulatory system.

The synthesized foam features a re-entrant structure that integrates hard domains for structural integrity with soft domains for elasticity (Figure 1b). Unlike conventional materials, auxetics expand under tension, providing superior shock absorption and pressure relief. The data confirmed that significant performance differences exist across heterogeneous neuropathic conditions. While GRF reductions in Subjects A, D, and F highlight the material's potential for pressure attenuation, instances of increased GRFs in other subjects were likely driven by confounding variables, such as increased gait velocity or the absence of standard mobility aids, rather than material failure. Ultimately, the auxetic foam enhanced gait symmetry for all participants, suggesting benefits beyond simple force reduction that include improved proprioceptive control and overall system stability.

Qualitative Findings

Qualitatively, the auxetic foam insoles significantly enhanced gait by providing superior support and facilitating a more natural heel-to-toe weight transfer.

- Subject A (Diabetic Neuropathy): Transitioned from an antalgic, "twisted" walk with frequent pauses to a fluid, natural gait (Figure 6).
- Subject B (Cancer-related Neuropathy): Showed a reduction in a pre-existing limp, though pauses remained due to the absence of their usual walking sticks.
- Subject C (Diabetic Neuropathy): Exhibited improved weight distribution, though a swifter walking pace resulted in higher recorded forces.
- Subject D (Arthritic Neuropathy): Corrected a steppage gait; instead of landing on the toes, the subject achieved a midfoot-to-heel strike, resulting in a visible improvement in coordination and reduced GRFs (Figure 7).
- Subject E (Control): Displayed greater stability and control despite an increase in force due to a naturally rapid cadence.
- Subject F (Injury-related Neuropathy): Showed a reduction in steppage gait characteristics, gaining more stability from the material's conforming properties.



Figure 6. Auxetic foam material improved gait cycle of Subject A with Diabetic Neuropathy.

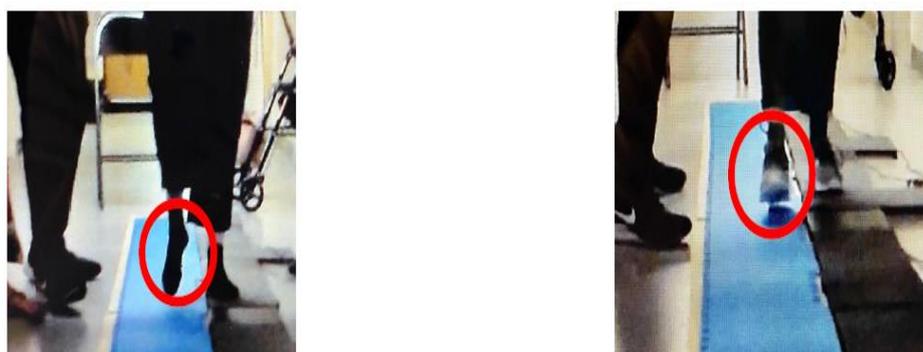


Figure 7. Auxetic foam material improved gait cycle of Subject D with Neuropathic arthritis.

Limitations and Future Research

This study represents an initial feasibility investigation; thus, the auxetic foam material remains exploratory. In addition to the small sample size, the findings have several limitations. The participant cohort provided only a narrow representation of the broader neuropathic population. Future research should include a larger, more diverse population that varies in age, duration of symptoms, and the specific etiologies of cancer, diabetes, or injury that led to neuropathy. Recruitment challenges due to participants' occupational demands were also noted.

Furthermore, discerning the precise root causes of neuropathy proved challenging when participants presented with potential dual etiologies (e.g., Subject D attributed their condition primarily to arthritis but also had a history of cancer). Such confounding variables complicate the ability to definitively pinpoint the neuropathic cause.

Future iterations of this research should focus on the specificities of these variables (e.g., type 1 vs. type 2 diabetes, type of cancer, nature of injury) during the assessment. Additionally, incorporating more kinematic assessments would allow for an analysis of the auxetic foam's impact on targeted muscle groups. These steps are necessary to inform the improved design of orthoses for diverse neuropathic conditions.

5. Conclusions

The auxetic foam material proved to be an effective aid in reducing peak vertical GRFs in a subset of neuropathic participants and improving gait cycles across various neuropathic subtypes compared to standard OTC insoles. While the effectiveness varied among subjects, the auxetic foam consistently enhanced comfort and stability for all participants. Overall, the study demonstrated both kinematic and kinetic improvements, warranting further investigation into this promising orthotic material.

Author Contributions: Conceptualization, L.B.; Methodology, L.B., C.Z., E.J. and S.P.; Software, L.B. and C.Z.; Validation, L.B., C.Z., E.J., and S.P.; Formal Analysis, L.B.; Investigation, L.B., C.Z., E.J., and S.P.; Resources, L.B., C.Z. and E.J.; Data Curation, L.B.; Writing – Original Draft Preparation, L.B. and C.Z. ; Writing – Review & Editing, L.B., C.Z., E.J., and S.P.; Supervision, L.B., C.Z., E.J., and S.P; Project Administration, L.B.

Funding: This research was funded by NASA/MSFC, grant number 80NSSC20M0247 and via in-kind resources by the Department of Industrial and Manufacturing Engineering and High-Performance Materials Institute at Florida Agricultural and Mechanical University under Grant 80NSSC20M0247.

Data Availability Statement: The data related to these studies is available on request from the Corresponding Author.

Acknowledgments: This work was supported by NASA/MSFC, University of Alabama Birmingham(UAB) College of Engineering, and Florida Agricultural and Mechanical University-Florida State University (FAMU-FSU) College of Industrial and Manufacturing Engineering. This work included contributions to the material study design and analysis and CAD analysis from the NASA EM and ES Engineering branches, in which acknowledgement is attributed to Enrique Jackson, Charles D. Wingard, Kevin Young, Leslie Alexander, Barbara Breithaupt, and Eleanor Dickens.

Other acknowledgements are attributed to NASA-MSFC's former interns and Small Business Technical Coordinator as follows: Danyale Berry (DB), Clarke Miley (CM), Kyra Lee (KL), Chase Robinson, (CR), Ihsaan El-Amin (IE), McKenzie Davis (MD), Laurence Price-Webb (LP, and Angela Lovelady.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

GRF	Ground reaction force
NASA	National Aeronautics Space Administration
MSFC	Marshall Space Flight Center
OTC	Over-the-counter

Appendix A

GRFS data(In Newtons(N)); Subjects A, B, D, E, and F(with braces)					
Group	Cancer	Diabetes	Disease	Control	Injury
Barefoot	771	918	817	689	912
	804	938	802	697	864
	800	943	466	698	896
	793	953	784	690	902

	761	923	811	667	892
	793	956	779	665	893
No auxetic	764	963	712	709	794
	783	990	798	703	836
	798	963	765	432	951
	790	969	792	388	953
	767	929	787	610	965
	797	974	775	730	932
Auxetic	796	957	777	774	944
	826	961	772	674	935
	793	939	756	729	981
	784	925	757	709	908
	790	955	572	738	883
	783	958	784	714	932

Table A2. Vertical Ground Reaction Forces (GRFs) Data in Newtons (N) for Subjects A, B, D, E, and F(with braces).

Table A2 presents the vertical ground reaction forces (GRFs) measured in Newtons (N) for Subjects A, B, D, E, and F (F used braces). Data is grouped into three conditions: barefoot walking, walking with standard insoles ("No auxetic"), and walking with experimental auxetic foam insoles ("Auxetic"). Subject C is excluded from this table to isolate specific neuropathic categories, with Subject A serving as the representative for diabetic neuropathy in this analysis.

Table A3. Vertical Ground Reaction Forces (GRFs) Data in Newtons (N) for Subjects A, B, D, E, and F(without braces).

GRFS data(In Newtons(N)); Subjects A, B, D, E, and F(without braces)					
Group	Cancer	Diabetes	Disease	Control	Injury
Barefoot	771	918	817	689	912
	804	938	802	697	864
	800	943	466	698	896
	793	953	784	690	902
	761	923	811	667	892
	793	956	779	665	893
No auxetic	764	963	712	709	794
	783	990	798	703	836
	798	963	765	432	951
	790	969	792	388	953
	767	929	787	610	965
	797	974	775	730	932

Auxetic	796	957	777	774	807
	826	961	772	674	935
	793	939	756	729	631
	784	925	757	709	856
	790	955	572	738	779
	783	958	784	714	832

Table A3 presents the vertical ground reaction forces (GRFs) measured in Newtons (N) for subjects A, B, D, E, and F. This data specifically focuses on conditions where Subject F used no braces. The data is grouped into three conditions: barefoot walking, walking with standard insoles ("No auxetic"), and walking with experimental auxetic foam insoles ("Auxetic"). Subject C is excluded from this table to isolate specific neuropathic categories, with Subject A serving as the representative for diabetic neuropathy in this analysis.

Table A4. Vertical Ground Reaction Forces (GRFs) Data in Newtons (N) for Subjects B, C, D, E, and F(with braces).

GRFS data (In Newtons(N)); Subjects B, C, D, E, and F(with braces)					
Group	Cancer	Diabetes	Disease	Control	Injury
Barefoot	771	1119	817	689	912
	804	1095	802	697	864
	800	1165	466	698	896
	793	1148	784	690	902
	761	1102	811	667	892
	793	1078	779	665	893
No auxetic	764	1130	712	709	794
	783	1030	798	703	836
	798	1111	765	432	951
	790	1070	792	388	953
	767	1147	787	610	965
	797	1131	775	730	932
Auxetic	796	1106	777	774	944
	826	1145	772	674	935
	793	1121	756	729	981
	784	1098	757	709	908
	790	1127	572	738	883
	783	1116	784	714	932

Table A4 presents the vertical ground reaction forces (GRFs) measured in Newtons (N) for Subjects B, C, D, E, and F (with braces). Data is grouped into three conditions: barefoot walking, walking with standard insoles ("No auxetic"), and walking with experimental auxetic foam insoles ("Auxetic"). Subject A is excluded from this table to isolate specific neuropathic categories, with Subject C serving as the representative for diabetic neuropathy in this analysis.

Table A5. Vertical Ground Reaction Forces (GRFs) Data in Newtons (N) for Subjects B, C, D, E, and F(without braces).

GRFS data (In Newtons(N)); Subjects B, C, D, E, and F(without braces)					
Group	Cancer	Diabetes	Disease	Control	Injury
Barefoot	771	1119	817	689	912
	804	1095	802	697	864
	800	1165	466	698	896
	793	1148	784	690	902
	761	1102	811	667	892
	793	1078	779	665	893
No auxetic	764	1130	712	709	794
	783	1030	798	703	836
	798	1111	765	432	951
	790	1070	792	388	953
	767	1147	787	610	965
	797	1131	775	730	932
Auxetic	796	1106	777	774	807
	826	1145	772	674	935
	793	1121	756	729	631
	784	1098	757	709	856
	790	1127	572	738	779
	783	1116	784	714	832

Table A5 presents the vertical ground reaction forces (GRFs) measured in Newtons (N) for Subjects B, C, D, E, and F (without braces). Data is grouped into three conditions: barefoot walking, walking with standard insoles ("No auxetic"), and walking with experimental auxetic foam insoles ("Auxetic"). Subject A is excluded from this table to isolate specific neuropathic categories, with Subject C serving as the representative for diabetic neuropathy in this analysis.

Table A6. Kruskal-Wallis and Dunn's post-hoc test results for Subjects A, B, D, E, and F (braced condition).

KRUSKAL-WALLIS	Observed Value	192.254
	Critical Value	5.991
	p	<0.0001
	Degrees of Freedom	2
	alpha	0.05
	<i>K</i>	
	<i>p</i> <0.0001	
PAIRWISE COMPARISONS	Insole vs. Neuropathy	Significant*
	<i>p</i>	0.002
		<i>p</i> =0.002

	Insole vs. GRFS	Significant*
	p	<0.0001
		$p < 0.0001$
	Neuropathy vs. GRFS	Significant*
	p	<0.0001
		$p < 0.0001$

Table A6 Results were significant ($p < .0001$) at the $\alpha = 0.05$ level. Data from Subject C (diabetic neuropathy) were excluded to maintain a balanced assessment of various neuropathic etiologies, as diabetic neuropathy was already represented by Subject A.

Table A7. Kruskal-Wallis and Dunn's post-hoc test results for Subjects A, B, D, E, and F (without braces).

KRUSKAL-WALLIS	Observed Value	192.254
	Critical Value	5.991
	p	<0.0001
	Degrees of Freedom	2
	alpha	0.05
	<i>K</i>	
		$p < 0.0001$
PAIRWISE COMPARISONS	Insole vs. Neuropathy	Significant*
	p	0.002
		$p = 0.002$
	Insole vs. GRFS	Significant*
	p	<0.0001
		$p < 0.0001$
	Neuropathy vs. GRFS	Significant*
	p	<0.0001
		$p < 0.0001$

Table A7 Results were significant ($p < .0001$) at the $\alpha = 0.05$ level. Data from Subject C (diabetic neuropathy) were excluded to maintain a balanced assessment of various neuropathic etiologies, as diabetic neuropathy was already represented by Subject A.

Table A8. Kruskal-Wallis and Dunn's post-hoc test results for Subjects B,C, D, E, and F (braced condition).

KRUSKAL-WALLIS	Observed Value	192.254
	Critical Value	5.991
	p	<0.0001
	Degrees of Freedom	2
	alpha	0.05
	<i>K</i>	
		$p < 0.0001$
PAIRWISE COMPARISONS	Insole vs. Neuropathy	Significant*

	p	0.002
		$p=0.002$
	Insole vs. GRFS	Significant*
	p	<0.0001
		$p<0.0001$
	Neuropathy vs. GRFS	Significant*
	p	<0.0001
		$p<0.0001$

Table A8 Results were significant ($p < .0001$) at the $\alpha = 0.05$ level. Data from Subject A (diabetic neuropathy) were excluded to maintain a balanced assessment of various neuropathic etiologies, as diabetic neuropathy was already represented by Subject C.

Table A9. Kruskal-Wallis and Dunn's post-hoc test results for Subjects B,C, D, E, and F (without braces).

KRUSKAL-WALLIS	Observed Value	192.254
	Critical Value	5.991
	p	<0.0001
	Degrees of Freedom	2
	alpha	0.05
	<i>K</i>	
		$p<0.0001$
PAIRWISE COMPARISONS	Insole vs. Neuropathy	Significant*
	p	0.002
		$p=0.002$
	Insole vs. GRFS	Significant*
	p	<0.0001
		$p<0.0001$
	Neuropathy vs. GRFS	Significant*
p	<0.0001	
		$p<0.0001$

Table A9 Results were significant ($p < .0001$) at the $\alpha = 0.05$ level. Data from Subject A (diabetic neuropathy) were excluded to maintain a balanced assessment of various neuropathic etiologies, as diabetic neuropathy was already represented by Subject C.

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