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Design and testing of a prototype foot orthosis that uses the principle of granular jamming

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Abstract

Study Design: A mechanical testing protocol was used to compare the material properties of commercially available foams with that of a newly designed granular jamming orthosis prototypes.

Background: Foot orthoses have an inherent limitation of predetermined mechanical material properties coupled with a fixed orthotic interface shape that cannot be readily changed.

Objectives: To develop and test a novel orthotic insole design concept that incorporates principles of granular jamming.

Methods: Granular media were used in combination with vacuum pressure to create a variable stiffness granular foot orthosis. Four types of granular media (rice, poppy seeds, micropolystyrene, and polystyrene beads) were tested in different prototype configurations varying in volume fill and particulate size. Stress–strain curves were obtained from uniaxial compression tests to characterize granular foot orthosis prototypes in comparison with commercial orthotic foams.

Results: Increasing vacuum pressure increased prototype stiffness for most configurations. A single granular jamming orthosis could exhibit energy absorption values that spanned the entire commercial foam performance range, and in some cases extended far beyond the upper values of the tested foams.

Conclusion: The results suggest that granular jamming principles can provide clinicians the capability for rapid selection of mechanical properties over a wide range of orthosis stiffnesses. Importantly, patients could don the orthosis because the clinician makes real-time assessments and adjustments in the clinic.

Keywords

foot orthosis, granular jamming, dilatancy, vacuum pressure, compression test

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Background

Orthoses are generally designed for a specific purpose based on factors such as expected loading of a region.[1,2] For custom-molded foot orthoses, shape capture of the plantar surface is required, where interface shape and material properties are predetermined for the treatment period. Changes in orthotic management often require fabrication of an entirely new orthosis, which is time-consuming and costly.[3,4] A solution for quick alteration of shape and mechanical properties would be a major clinical advancement for orthotic treatment. Here, we present the design and testing of an adjustable granular jamming foot orthosis prototype.

We hypothesized that granular jamming would allow a single orthosis to exhibit a range of material properties. Granular jamming refers to a material phase transition where a fluid-like granular medium (e.g. sand) becomes rigid.[5] Here, we focus on packing fraction, which relates to granular density and is a key parameter influencing transition into a jammed state. One can increase packing fraction by reducing container volume by evacuating the air around the granules. Granular jamming includes phenomena such as dilatancy, which has been used in previous prosthetic and orthotic applications.[6,7] Vacuum casting with sand can accelerate the fabrication process in prosthetics and orthotics.[6] Granular jamming principles have also been leveraged in soft robotics because of its rapid shape matching and phase transitioning characteristics.[8] Granular jamming principles have not been explored to alter and control the material properties of a foot orthosis.

The mechanical response and impact absorption properties of a prototype granular orthosis were compared with commercially available orthotic foams. Foam mechanical behavior is very different from that of solid materials. On compression, a foam initially behaves linearly and elastically with an elastic modulus, E. This modulus is valid until its elastic limit, characterized by the foam cell walls yielding. The foam then enters a second region where it can be compressed at a near constant stress, called the plateau stress. A third region begins when the cell walls collapse to a point of densification. At this point, mechanical stress rises rapidly. Densification strain is considered a critical strain where the material begins to fail and cannot recover to its original state (Supplemental Digital Content 1, S1, http://links.lww.com/POI/A32).

Two main performance measures of an orthotic material are its cushioning and impact absorption. Proper manipulation of properties influencing these measures should provide predictable control over orthosis function. Here, we tested energy absorption because of its direct relationship with load response in

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characterizing foot orthosis design and performance (Supplemental Digital Content 1, S2, http://links.lww.com/POI/A32).[9]

Methods

Granular orthosis detailed design

We identified four major design constraints of a granular orthosis through user surveys; these include the ability to (1) maintain desired air pressure for an extended duration, (2) adjust air pressure to various levels, (3) sense internal pressure, and (4) return to its original shape after vacuum pressure is released. The experimental setup (Figure 1, Supplemental Digital Content 1, S3, http://links.lww.com/POI/A32) includes two subsystems: bladder/valve system (i.e. granular foot orthosis prototype) and pressure control system. The granular foot orthosis consisted of two rectangular bladders (108 × 273 mm): a nylon fabric internal breathable bladder (Lycra, DuPont, Wilmington, DE, USA) and an airtight polyvinyl chloride sheet outer bladder (Transparent Inflatable Tube 59260EP, Intex, Long Beach, CA, USA). The breathable inner bladder allowed air between the inner granules to be evacuated and prevented clogging of the tubing. It was filled to a specified volume with granular material and sewn shut. The airtight outer bladder was sealed around the inner bladder, with the external tubing and stopcock valve. The granular orthosis was detached from the pressure control system once desired vacuum level was achieved and the valve closed. Because composition of bladders was controlled across all prototypes, any observed differences were due to different fill characteristics or vacuum pressures across testing conditions.

Four different granular media were used (Supplemental Digital Content, S3, http://links.lww.com/POI/A32) to test the effects of size, shape, and material of granular particles on orthosis function: micropolystyrene beads (1.2 mm dia.), polystyrene beads (4.4 mm dia.), poppy seeds (~0.8 mm dia.), and rice (~5 × 2 mm). Polystyrene beads were selected as the primary granular medium because they are lightweight, compliant, readily available, and cost-effective. They were used to test the effects of volume fill (low: 300–325 mL, medium: 375–400 mL, high: 450–500 mL) and granule size. Poppy seeds and rice were used to test stiffer granules of different sizes. We also examined whether we could mimic energy absorption characteristics of several commercially available foams by altering internal pressure to tune granular orthosis density and material properties.[7] Further details about the pressure-control system can be found in Supplemental Digital Content 1, S3 (http://links.lww.com/POI/A32).

Testing protocols

Our focus was to test performance under compression because it is a primary loading condition for foot orthoses. The rectangular prototype approximated a US 10.5 men's shoe size. Test specimen thicknesses were within the range of common orthoses (6–19 mm), but thinner than typical materials testing standards (ASTM D1621-16, D3575-14).[10,11] We modified the standard test protocol with a slightly lower deflection (10%) to ensure that custom-sized test plates did not contact each other during testing. Seven common commercial foams were also tested (Supplemental Digital Content 1, S3, http://links.lww.com/POI/A32). Because densification failure was never observed in the granular orthoses, a second crush protocol was performed to examine prototype failure strain.

Tests were performed in a materials testing machine (MTS 810, MTS Systems, Eden Prairie, MN, USA) at room temperature (20–21°C) and atmospheric pressure (Supplemental Digital Content 1, S3, http://links.lww.com/POI/A32). Time, force, displacement, and strain data were collected using displacement control at constant strain rates of 0.001 s^{-1} (low) and 0.1 s^{-1} (high). Each foam and prototype sample was tested to 10% deflection in our standard testing protocol. In total, 80 tests were conducted on eight granular orthosis prototypes, and 14 tests conducted on seven commercial materials (Table 1).

Energy absorption, U, was calculated for each sample as area under the stress–strain curve from test onset to densification strain.

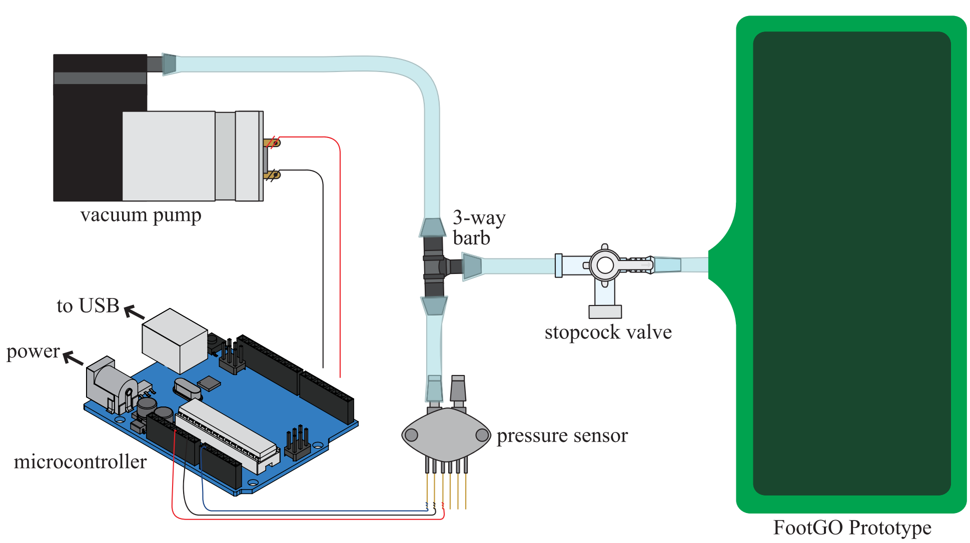

Figure 1. Schematic of foot granular orthosis prototype and pressure control system: This schematic includes a vacuum pump, microcontroller, pressure sensor, plastic barb fitting and tube system, and the granular orthosis prototype (bladders and valve)

Table 1. Testing conditions used for each granular foot orthosis prototype

Prototype	Granular material	Granular size	Volume fill	Negative pressures tested (kPa)	Strain rates tested (1/s)
P1	Polystyrene	Small	Large	−10 −15 −20	0.001 0.1
P2	Polystyrene	Small	Medium	−10 −15 −20	0.001 0.1
P3	Polystyrene	Small	Small	−10 −15 −20	0.001 0.1
P4	Polystyrene	Large	Large	−10 −15 −20	0.001 0.1
P5	Polystyrene	Large	Medium	−10 −15 −20	0.001 0.1
P6	Polystyrene	Large	Small	−10 −15 −20	0.001 0.1
P7	Poppy seeds	Small	Large	−10 −20	0.001 0.1
P8	Rice	Large	Large	−10 −20	0.001 0.1

The foams were limited by their densification, whereas granular orthoses never reached a failure point during the standard testing protocol. Energy absorption for granular orthosis prototypes was therefore calculated twice, with a limit equal to the measured minimum foam densification strain (0.011), and again with a limit of maximum foam densification strain (0.067). This provided energy absorption values corresponding to the failure bounds of the most compliant and stiffest foams.

Results

Each granular foot orthosis prototype could be adjusted to match the range of behaviors exhibited by the commercial foams (Figure 2). More negative pressure resulted in increased stiffness for high volume fill prototypes. Other prototype configurations were not as predictable in the pressure–stiffness relationship (Table 2).

Maximum and failure strains observed for granular orthoses were always greater than those measured for commercial foams (Figure 3). The smallest maximum strain value from a granular orthosis (poppy seed) was still greater than the highest failure strain of the commercial foams (Plastazote). Comparing foam failure strains with the granular orthosis crush tests, the lowest strain to failure of the granular orthosis (polystyrene microbeads and small volume) was more than three-fold larger than the maximum failure strain of the tested foams, and 18 times as large as the minimum failure strain among the foam specimens. Thus, the granular orthoses could experience greater deformation without reaching failure compared with the foams.

By adjusting internal negative pressure, each prototype could span the full range of energy absorption observed for all foams tested (Supplemental Digital Content 1, S4, http://links.lww.com/POI/A32). To compare the performance of granular orthoses relative to that of commercial foams, the prototype energy absorption was calculated with integration bounds specific to the minimum and maximum foam failure points.

Table 2. Prototype configurations that exhibit consistent stiffness versus pressure relationship

	Volume fill		
	Low	Medium	High
Low strain rate			
Bead size			
Small	Not consistent	Consistent	Consistent
Large	Not consistent	Not consistent	Not consistent
High strain rate			
Bead size			
Small	Not consistent	Not consistent	Consistent
Large	Consistent	Consistent	Consistent

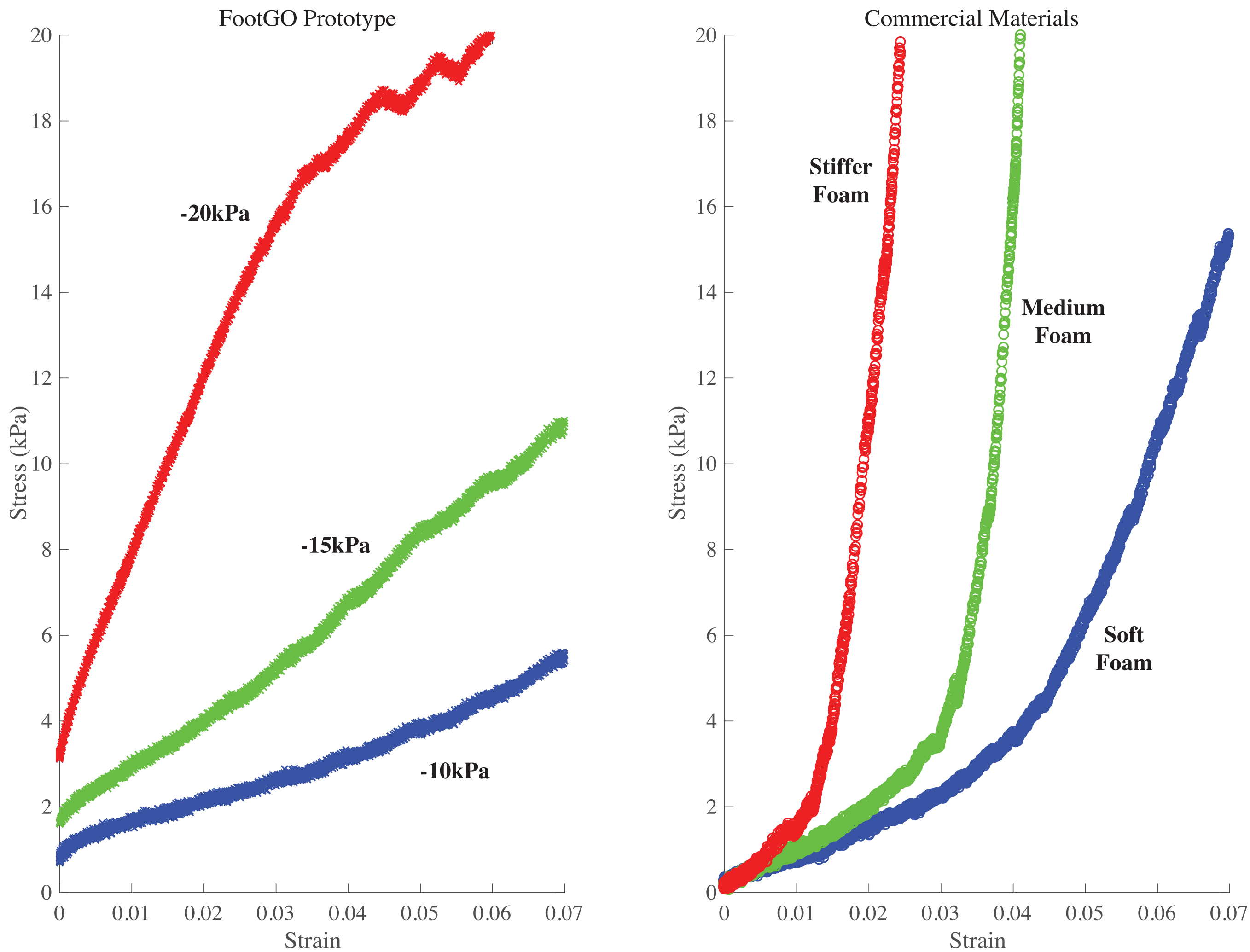

Figure 2. Representative stress–strain behaviors in the linear ranges of (A) single foot granular orthosis prototype under three different negative pressures and (B) three representative commercial foams at a high strain rate of 0.1. Increased negative pressure of the granular orthosis prototype resulted in corresponding increases in orthosis stiffness over this strain range. The commercial foams reached densification failure below the 10% maximum strain set for these tests. The prototype foot orthosis continued deforming well beyond the strain range depicted here, which is limited to the same range as the commercial foams for comparison

Integration bounds corresponded to minimum (0.011) and maximum (0.0673) strains to failure of foams tested. Granular foot orthosis foam energy absorption performance (FEAP) values were compared with the range of foam failure strains (Supplemental Digital Content 1, S4, http://links.lww.com/POI/A32). At low strain rate, the polystyrene microbead orthoses exhibited an energy absorption ranging from the low end to beyond the upper limit of the FEAP range. The poppy seed and rice granules had even greater energy absorption ranges. At higher negative pressures, the rice granule prototype's low end of energy absorption was located near the upper limit of the FEAP band and extended up to ~2800 J/m^3 (Supplemental Digital Content 1, Figure S4, http://links.lww.com/POI/A32). At high strain rate, prototype energy absorptions showed similar trends with changing negative pressure. At low pressure, the polystyrene microbead prototypes spanned ~75% of the FEAP band. At moderate pressure, these prototypes spanned ~90%. At high pressure (−20 kPa), the upper end of energy absorption for polystyrene microbead prototypes far exceeded those at lower negative pressures. The rice granule prototype range began near the upper limit of the FEAP band and extended to ~3500 J/m^3 (Supplemental Digital Content 1, Figures S4–S5, http://links.lww.com/POI/A32).

Discussion

A fundamental limitation of a foot orthosis is that clinicians are restricted to the single predetermined interface contour and material property they prescribe. Here, we demonstrate a granular jamming orthosis whose material properties were rapidly modulated over a broad range. This would allow iterative modifications of a single device in the clinic that could be useful for frequently changing foot conditions and disorders, such as the treatment of plantar pressure ulcers because of diabetes.

Under our standard testing protocol, commercial foams exhibited the expected stress–strain behavior similar to the generalized foam model curve. The slopes of the stress–strain curves within its linear region increased for stiffer foam materials as expected. Stress and energy absorption of the commercial foams predictably increased with increasing strain rate.[12] Using commercial foam samples as a standard for comparison, our data

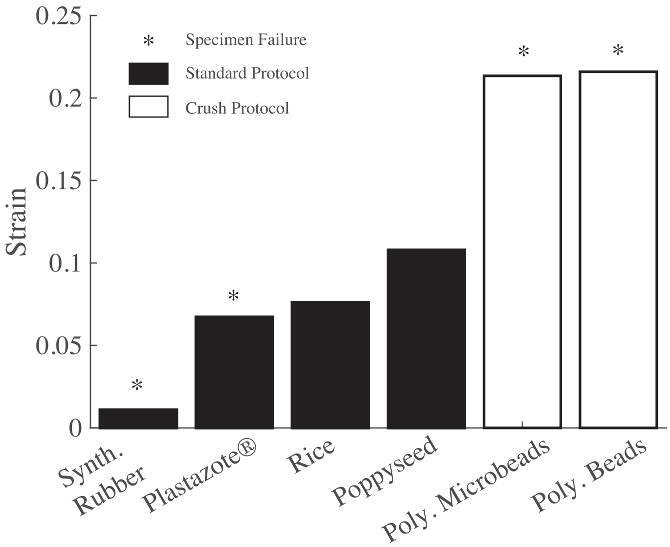

Figure 3. Maximum or failure strains reached under standard (black bars) and crush (white bars) testing protocols. Under the standard protocol, specimens were compressed until either a predefined strain limit or time limit was reached. Synthetic Rubber and Plastazote are shown as representatives of the foams with the minimum and maximum strains to failure, respectively. Synthetic Rubber and Plastazote reached failure (densification, indicated by asterisk), whereas the granular orthosis prototypes did not. Granular orthosis prototypes were then compressed to failure under a separate crush protocol (white bars), reaching failure strains approximately 18 times greater than the minimum foam failure strain and 3 times greater than the maximum foam failure strain

support the validity of this compression testing protocol to assess the stress–strain curves of the different granular orthosis prototypes.

A variety of factors can affect granular orthosis stiffness and its response to vacuum pressure. Each prototype became stiffer because vacuum pressure increased within the inner bladder. Higher vacuum pressures resulted in prototypes experiencing greater stress and absorbing more energy at a given strain, which is consistent with the behavior of stiffer materials.[13] Greater volume fill and smaller bead size most consistently exhibited these trends. Rice and poppy seed granules demonstrated expected responses to vacuum pressure under all conditions. Individual rice and poppy seed granules are stiffer than polystyrene and also resulted in a greater range of aggregate stiffness. A wide range of configurations that emulate or surpass the performance of multiple commercial foams is possible from a single orthosis using granular jamming principles.

Granular orthoses had much higher failure strains than commercial foams. The foams failed well before the 10% target strain, whereas granular orthoses never failed within standard testing parameters. Substantially more strain was required to cause failure in granular orthoses using the crush protocol. The energy absorption performance range of the polystyrene-filled prototypes increased with increasing negative pressure because the orthosis stiffness increased, delivering a high level of control over its material properties. Foot orthosis stiffness should be optimized to an individual's foot characteristics to obtain the greatest pressure reduction.[14,15] The different stiffness values observed here could represent an orthotic treatment to differentially protect sensitive areas of the foot. Careful monitoring with appropriate foot orthosis stiffness modulation could lead to greater comfort and increased activity level, potentially reducing rehabilitation and recovery time.

Several factors limit the scope and conclusions of our work. First, we only quantified the material properties of granular orthoses. Although there are benefits to the shape-matching ability of granular jamming orthoses, we did not test this against traditional fabrication processes. We also did not study the impact or cyclical loading to assess device durability. Finally, more research is needed to test foot–orthosis interactions *in situ* during normal activities of daily living.

Conclusions

A prototype granular jamming foot orthosis exceeded the strain to failure of commercial foams and could rapidly adjust its material properties. Granular orthosis energy absorption values were similar to both compliant and stiffer foams. This versatility in performance offers several suitable user applications (e.g. standing, walking, running, and jumping) from a single orthotic device. A design with multiple granular media cells could also deliver differential properties across different regions of the foot. The need for multiple custom orthoses per patient could be reduced or eliminated with a granular jamming orthosis that can be adjusted and readjusted to match desired properties.

Author contributions

The authors disclosed the following roles as contributors to this article: Y.H.C. came up with the original idea for the device. E.S. developed the prototypes, testing protocols, and executed the data collections and analyses. Y.H.C., G.K., and J.C. advised E.S. on all aspects of the study. All co-authors contributed to the preparation of this article.

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Declaration of conflicting interests

The author disclosed the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: The authors have filed a patent on the granular jamming foot orthotic device tested in this study. The authors have no current plans to commercialize the technology. The Georgia Institute of Technology owns the patent and licensing rights.

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