

Adaptive Midsole

Granular Convection for Use-Activated Custom Footwear

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ABSTRACT

The Adaptive Midsole is a footwear technology that utilizes granular convection to adapt to an athlete's unique footstrike. Granular convection is a phenomenon where particles of different size and morphology self-sort when they are agitated. This research is part of an initiative to develop footwear that evolves over time to deliver individualized performance. It seeks to address two significant challenges in footwear: a growing need for individual customization and the complexity of mass-producing customized products.

This paper outlines prototypes that evolved from an undifferentiated state, into a unique pattern of cushioning and structure through use. It investigates granular convection, including container and particle design, and its response within a midsole over approximately 20,000 strides, equivalent to a full marathon. A series of wear tests demonstrated that a 1:1:1 ratio of large regular foam beads, to small regular foam beads, to irregular rubber particles achieved the best effect, whereby softer particles moved up to cushion points of impact, while stiffer particles moved below to provide structure. The prototype was printed in silicone to withstand repeated compressions while maintaining necessary flexibility and strength. The results validate our hypothesis that the right combination of particles and flexible materials can deliver a repeatable, adaptive response with granular convection in a midsole. This paper also suggests future research directions in particle morphology, and the design of the midsole container. This study not only introduces an original adaptive technology but offers a design and manufacturing approach for the future of personalized athletic footwear.

- 1 Close-up of the Adaptive Midsole after user testing. The large, regular foam beads can be observed to have moved to cushion the heel.
- 2 Shoe prototype wearing test.

INTRODUCTION

Footwear traditionally relies on a static approach to material performance, creating shoes tailored for specific anatomies and uses, such as particular sports or movements. While these designs cater to general requirements, they often fail to meet the individual needs of athletes. Similarly, standard sizing does not account for variations in foot shape, gait patterns, and pressure points, potentially leading to discomfort and suboptimal performance, especially in high-demand athletic activities.

Recent advances in computer-controlled knitting and additive manufacturing promise fully customized footwear, tailoring every aspect of a shoe to the user's specifications (Ozdemir, Cascini, and Verlinden 2020; Ghimouz, Kenné, and Hof 2023). However, these methods present significant challenges. Individual tailoring complicates the manufacturing process, making it time-consuming and costly. Additionally, these technologies deviate from conventional manufacturing practices, leading to difficulties in matching custom performance and achieving commercially viable production volumes.

This project adopts a different approach to customization, instead of designing shoes that are personalized at the point of manufacturing, the Adaptive Midsole is designed to be produced generically, but with the ability to adapt to an athlete's unique pattern of use. The Adaptive Midsole is the result of a year-long collaboration between our research group and a major footwear brand, with the aim of leveraging the dynamics of granular convection to deliver on the promise of adaptive footwear. This research is part of an overall initiative to develop footwear that evolves and improves over time for individualized performance.

This need for individually tailored footwear stems from the fact that athletes exhibit a wide variety of foot strike patterns, where a combination of anatomy and running styles result in a highly unique distribution of forces across the foot, and also the rest of the leg (Larson et al. 2011). Targeted cushioning and support thus become vital in mitigating the stresses experienced by the athlete's foot, to not only enhance performance, but to reduce the risk of injury (Aguinaldo and Mahar 2003; Asplund and Brown 2005). The midsole plays an important role in this regard, offering an opportunity to introduce softer cushioning directly below the foot to support the athlete, whilst mitigating the impact with a hard running surface (Bates 1989; Keller et al. 1996; Kerdok et al. 2002).

In this context, the Adaptive Midsole accommodates a wide array of foot anatomies and strides within the same



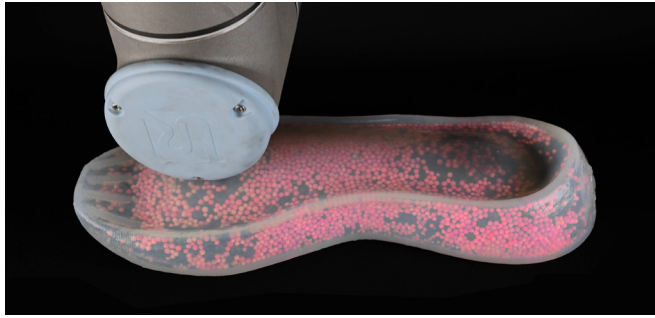
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assembly, evolving over the span of approximately 20,000 strides, equivalent to a full marathon, to an athlete's specific anatomy and movement style. Through this duration of use, the midsole transitions from a neutral, undifferentiated state to one providing selective cushioning and support tailored to the athlete's foot.

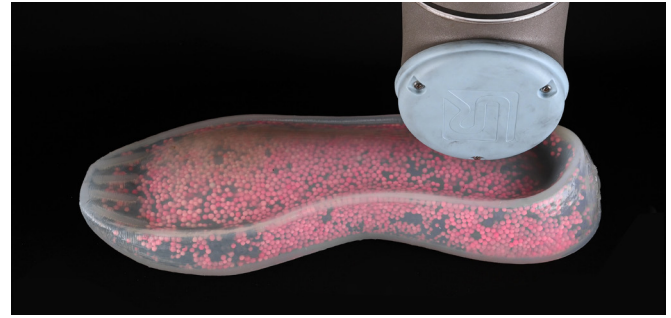
At the core of this innovation is granular convection, often referred to as the "Brazil Nut effect." This occurs when particles of different morphologies are agitated, resulting in a self-sorting effect (Rosato et al. 1987). Typically, larger particles move upwards towards the surface, whilst smaller particles move downwards. The regularity of particles also factors into their rise through the mixture; regularly shaped particles tend to rise at a consistent rate, where irregularly shaped particles have particular, stable orientations where their rise is dramatically reduced (Gajjar et al. 2021).

This paper explores the experimental process of applying and validating granular convection within the midsole and discusses the primary parameters that influence its effectiveness. The research pursued two interconnected design objectives: the shape and material of the particles within the midsole, which affect the occurrence and rate of granular convection, and the design and material of the flexible midsole "container" housing the particles, influencing the localized responsiveness of granular convection and the overall performance of the midsole.

The research was conducted with several assumptions and limitations, using available materials and technologies. Instead of developing specific materials for the particles or their container, the focus was on designing the interaction between the two to achieve meaningful granular convection within a midsole. The successful prototyping of the *Adaptive Midsole* (Figures 1, 2) opens avenues for further research that could refine the material properties of the particles and the container, leading to benefits such as improved



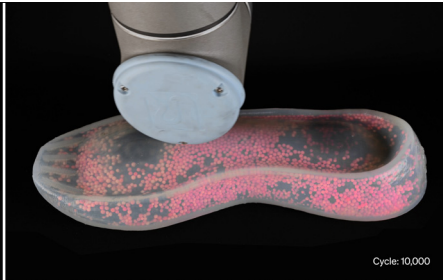
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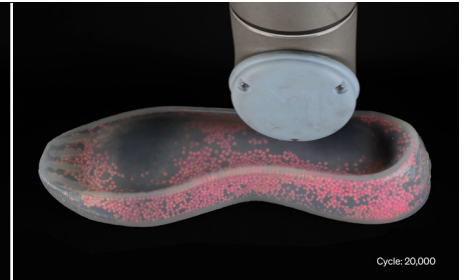
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Cycle: 0



Cycle: 10,000



Cycle: 20,000

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sustainability, reusability, and manufacturing viability.

State of the Art

Granular convection may be largely categorized into two states: vibro-fluidized and non-vibro-fluidized (Kudrolli 2004). In a vibro-fluidized state, particles are continuously agitated vertically, resulting in fluid-like behavior, similar to sand behaving like a fluid when vibrated. The opposite occurs with longer agitation cycles, where particles remain in contact longer. For a shoe midsole, granular convection is unlikely to achieve a vibro-fluidized state due to the vibration frequency.

Literature review indicates that the most important variables affecting granular convection are geometric: particle size and shape, and container geometry, which influence particle friction during convection (Kudrolli 2004). Density also affects convection to a lesser degree and is also less intuitive in its application. For example, in vibro-fluidized states, larger, lower-density particles take longer to rise to the surface of the mixture (Möbius et al. 2001). For our experiment, we assumed this to have a minor effect and assumed interstitial gas density and humidity as constants.

Existing applications of granular material in footwear are typically within foams or undifferentiated states as cushioning mediums with air. These techniques often provide static cushioning using beads or granules, with some air captured in the assembly, purportedly to increase the comfort or performance of the shoe. For instance, Nike's Joyride features thousands of colorful TPE foam beads within its midsole (Burgess 2019). These beads are monolithic, with

identical material properties, and appear to be for visual appeal rather than function. The Joyride system aims to provide personalized cushioning through the positioning of four separate pods filled with beads but lacks performance personalization as the beads' properties remain unchanged throughout its use.

Puma's Jamming FUSEFIT Evolution Sneakers adopted a user-customization approach, encasing NRGY beads within a transparent TPU midsole. These beads provide adaptive cushioning in response to the user's striding motions, resulting in a jamming effect. This process offers more personalization compared to the Joyride, but does not offer active, performance-driven customization. For instance, the heel area of the midsole should ideally also absorb impact rather than jamming to increase stiffness.

Our research differentiates itself by leveraging granular convection principles for real-time customization, allowing not just macro-material design but also the dynamic reorganization of materials within a midsole. The premise of the technology is for a midsole to start as an undifferentiated assembly and evolve to suit its usage pattern, optimizing for cushioning and structure through informed particle selection. This particular approach was also chosen as it is better suited to standardized footwear production, delivering personalization from a standardized assembly.

For granular convection to occur at a scale appropriate for a midsole, it must be localized enough to affect specific foot areas and not the entire midsole. It should not require excessive force to activate and should occur within a reasonable

timeframe. Most granular convection studies assume regular particle containers and homogeneous effects, but our research incorporates these constraints to ensure meaningful application for footwear midsoles..

Methods

The Adaptive Midsole was developed to demonstrate granular convection's effects over a simulated marathon, providing selective cushioning and structure. In this research, 20,000 strides were used to approximate a full marathon for a 5' 8" to 6' tall runner at a 10-minute mile pace (Hoeger et al. 2008). Our research focused on two main areas: the composition of the particles in the midsole and the design and material of the flexible midsole container. As these two factors are highly interrelated in the overall design of the midsole, we pursued them simultaneously.

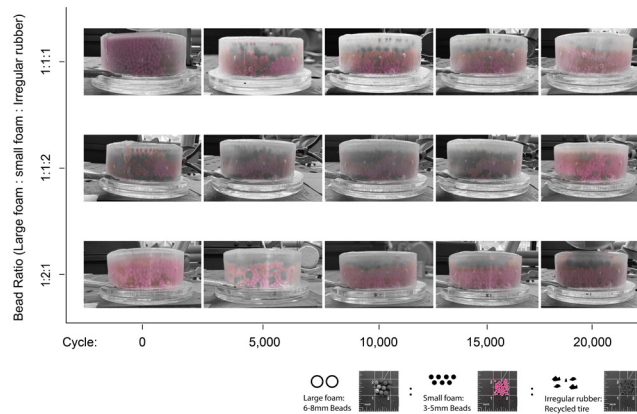
In testing a range of particles and a midsole shape design, this research adhered to the following design of the experiments. First, the particles were mixed into an undifferentiated state and placed in a testing container approximating a U.S. size 9 midsole. This midsole was then covered, secured, and subjected to 20,000 cycles of agitation, with periodic visual observations. A UR10 robot simulated the agitation, pressing down consistently on specific parts of the test container or midsole (Figures 3 through 5). Our goal was to demonstrate granular convection and show it could occur locally within the midsole, not uniformly. With the experiments using standard containers as well as in the full midsole, we aimed for a 3/16" depression during agitation.

Several principles guided our particle selection (Figure 6). At a high level, we needed particles that could provide cushioning by moving closer to points of impact, with more rigid particles forming a structure beneath. This generally meant selecting larger, regular-shaped particles made of softer materials and irregular-shaped particles of more rigid materials. Additionally, we also needed sufficient contrast in morphology to create noticeable granular convection without it happening uniformly across the midsole. Through empirical testing, we found that introducing a third particle type to buffer the interactions between the other two allowed us to better control the rate of granular convection.

Without a viable means to produce a variation of particles at the volume required for this research, the project focused primarily on commercially available particles. The particles tested consisted of expanded thermoplastic polyurethane and expanded polystyrene for more regular and softer particles, and different synthetic and natural rubber sources for more irregularly shaped particles. The regular and irregularly shaped particles selected were all within



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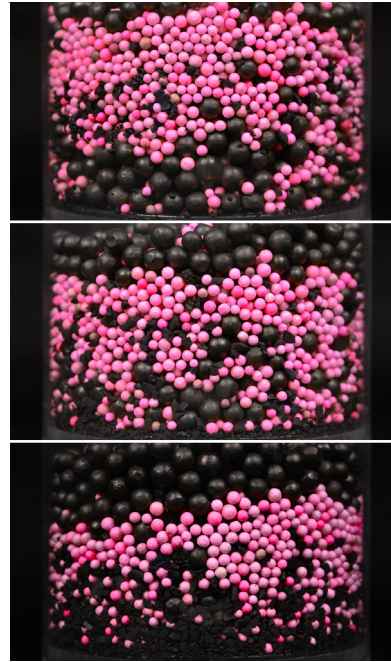


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- 3 Experimental setup of the final Adaptive Midsole design being agitated by a robotic arm with forefoot location of the midsole that were depressed in each cycle.
- 4 Heel location of the midsole that were depressed in each cycle.
- 5 Progression of granular convection at 0, 10,000, and 20,000 cycles in the process.
- 6 Survey of various particles that were experimented with, demonstrating the range of sizes, density, softness, and shapes considered.
- 7 Relative rates of granular convection in a three-particle system, in a flexible cylindrical test container. The width and depth of the container were designed to mimic the cross-section of a men's U.S. 9 midsole.

the range of approximately 2 to 8 mm in diameter. A visual recording was made to identify the granular convection in each experiment. By using different colors for the soft and rigid particles, the success of granular convection in each experiment was easily identified through visual inspection. If the colors did not shift from the homogenous state then granular convection did not take place, but if a solid cluster of any single color appeared, then that indicated that the soft particles organized themselves at the surface of the midsole.

After multiple rounds of experiments and down-selections, we identified three particle categories: large, regular-shaped foam particles (6-8 mm, relatively soft), small, regular foam



- 8 Test rigid cylinder with 1:1:1 mix of large regular, small regular, and irregular particles. As the particles move upwards towards the point of impact, they deliver more directed cushioning (left). From the top, the image shows the result of the 0, 10,000, 20,000 cycle cushioning test (right).
- 9 Two-point strike granular convection test with a soft silicon container.
- 10 Two-point strike test with a slanted interior bottom.
- 11 Two-point strike test with a slanted perimeter.
- 12 Two-point strike test with a center bump.

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particles (3-5 mm), and irregularly shaped rubber particles made from recycled tires (2-6 mm, harder and stiffer). These particles were cleaned to remove any dust or adhesive residue that might interfere with testing. Using these three groups of particles, we conducted further experiments to determine the optimal particle mixture ratio and its effect on granular convection.

In one definitive experiment, we tested different particle mix ratios (1:1:1, 1:1:2, 1:2:1) inside a translucent cylindrical silicone case (90 mm inner diameter, 60 mm height), subjected to 85 steps per minute (Figure 7). Visual analysis revealed that an excessive amount of irregular rubber particles led to granular jamming where particles would lock into a solid state, rather than the desired granular convection behavior, while an increased amount of small foam beads resulted in faster granular convection and the premature formation of a stratified arrangement earlier than the intended break-in period. The 1:1:1 ratio mix was ultimately chosen for the prototype.

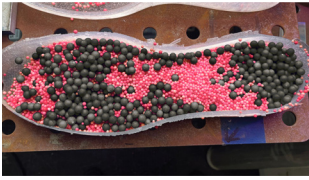
For the final midsole, the container needed to be flexible for cushioning, of sufficiently complex geometry for a shoe midsole, and have the ability to completely enclose the particles. We experimented with various designs and materials to see how different material properties and unique geometries affected granular convection. As a baseline, we used an acrylic cylindrical (90 mm diameter) for its low friction and transparency, with a thin plastic top boundary on which the agitation (Figure 8) was applied. In this container condition, we could be sure that granular

convection would reliably occur.

Transitioning to a flexible, midsole-shaped container revealed complications with regard to the material and fabrication of the container. With cast silicone, its tackiness often resulted in a build-up of dust, which hindered observation and convection. Moreover, it was challenging to produce sufficient geometric definition, and the material often yielded under repeated compression. Flexible resins printed via stereolithography (SLA) offered better resolution but lacked the necessary flexibility for a midsole. Stronger flexible resins provided the necessary strength but at the cost of reduced flexibility (Figure 15). In all of these container prototypes, we paired them with a flexible material as the top surface through which agitation was applied.

We eventually honed in on a solution to liquid print the midsole containers using a printing process called Rapid Liquid Printing. This method involved injecting a two-part silicone into a gel suspension substrate (Figure 13), creating a homogeneous object as layers bonded and cured together (Hajash et al. 2017a). This technique allowed rapid printing of complex shapes without support structures, producing a completely hollow midsole container with minimal post-processing.

While not the main research focus, this technique was crucial for achieving the right combination of precise geometry, flexibility, and strength needed for the Adaptive Midsole. We chose a translucent, lightweight silicone that could withstand repeated high-force agitation without failing (Figure



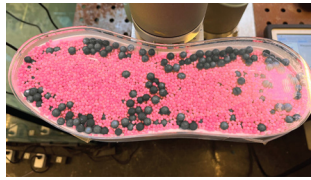
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13 Liquid-printed midsole suspended in the substrate during printing.

14 The chosen material exhibited sufficient transparency to observe granular convection.

15 Prototype of flexible SLA resin midsole. The edge detail allows it to be glued and loop-stitched.

16 Prototype of the chosen liquid printed midsole design.

14). The surface had low friction and tackiness, preventing adherence to itself or the particles. This method produced test containers for particle experiments and the final midsole prototype. We utilized this technique to make test containers (Figure 16) for experiments with the types and ratios of particles used, as well as for the eventual midsole prototype. For these, the containers were completely enclosed volumes, with the particles inserted through a small hole that was subsequently sealed with silicone..

RESULTS AND DISCUSSION

This project successfully demonstrated the functionality of a midsole that uses granular convection to provide adaptive cushioning and structure over the course of a simulated marathon. Additionally, we assembled a prototype shoe with a complete upper and outsole, with early user testing (Figure 17) proving the midsole's compatibility with other shoe components. While optimizing the assembly process and functional performance remains a future task, our final testing involved a men's US size 9 midsole, liquid-printed in silicone, and filled with a 1:1:1 ratio of particles. This final experiment showed visible and repeatable results over three sets of 20,000 cycles and exhibited responsiveness across different areas of the midsole (Figure 18).

Before final testing, the selection of the ratio of particles involved various experimental setups: flexible midsole-shaped containers with removable tops and cylindrical containers with both flexible and rigid walls (Figures 9 through 12). Although granular convection was demonstrable in the initial tests, concerns arose regarding visibility over time and the reliability of the flexible materials used. For example, the containers were often fouled by particles with poor color fastness, reducing their transparency. Additionally, cast and SLA-printed flexible materials wore out quickly under prolonged agitation, necessitating frequent replacement. Consequently, we conducted rapid, comparative tests using transparent, rigid containers until we resolved these issues in the final prototype.

Within the flexible containers, we determined that a 1:1:1 particle ratio achieved gradual and steady granular convection over 20,000 agitation cycles. We observed that increasing the proportion of smaller, regular beads accelerated the granular convection while increasing the proportion of irregular rubber beads slowed it down (Figure 7). Beyond a certain ratio, granular convection could also cease to occur. Our hypothesis for this behavior is that granular jamming occurs due to the irregular geometry of the rubber beads causing the mixture to essentially become rigid. This observation held true as we transitioned from small flexible test containers to the full midsole prototype.



17 Final shoe prototype under wear testing.

Despite achieving our primary goals, there is significant potential for further exploration. For example, future experiments might involve refining the morphology and surface conditions of the particles, as well as investigating various friction-controlling coatings on both the particles and the container. Varying particle shapes and surface treatments could also provide more nuanced control over granular convection. One other variable that was out of scope for the project, was the composition of the particle materials themselves. Future research could potentially explore particles of different densities and hardness levels for a broader range of midsole behaviors.

In the broader field of researching the physics of granular matter, it is also clear there is much more that remains to be understood with regard to granular convection. Further research might explore granular convection's peculiarities and variations, such as patterns of stratified structures using the Brazil Nut Effect and the Reverse Brazil Nut Effect (Breu et al. 2003). Variables like tap intensity, grain size, grain weight, and volume fraction of each granular species can be examined (Ludewig and Vandewalle 2005). The complexity of the mixture is another area for study, potentially revealing new phenomena beyond two- and three-particle systems. Much of current research also focuses on vertical vibrations in a vibro-fluidized state, and more can be done to understand the specific, low-frequency forces that occur within the midsole and the specific granular phenomena it creates (Kudrolli 2004a).

One of the more complex elements to design in this project was the flexible containers and the midsole container. Given that most applications of granular convection occur in regular geometries made of rigid materials, it was important to solve this challenge and create a flexible midsole container. Key criteria for our container material included tensile strength, hardness, weight, and transparency. Additionally, the fabrication method had to allow for a variety of geometries suitable for the design of a hollow midsole.

The liquid-printed silicone midsole emerged as the most suitable solution, offering significant advantages with rapid prototyping and mono-material recyclability. This process was faster and more reliable compared to cast silicone and was better suited for producing hollow, single-piece assemblies than SLA printing. Early prototypes with seams or two-part assemblies consistently failed, as it was challenging to find bonding methods that could match the flexibility and strength of the material. In contrast, the liquid-printed midsole's fill valve, sealed with silicone, remained intact across multiple experiments.

Further investigation into the material and geometric conditions of the midsole container revealed promising results. Early tests with concave and convex features on the container's interior (Figures 9 through 12) produced repeatable, localized patterns in granular convection. Local maxima on the bottom contour reduced granular convection around those areas, while slants or cambers created gradients in the granular convection. In addition, softer containers



18 Before (left)-and-after (right) of one wear test session.

generally increased the overall rate of convection. Another design element that was briefly explored was the incorporation of internal structures like columns and ties to fine-tune local responsiveness. As little research has explored these systematic morphological changes in container geometry, this could significantly enhance midsole design and provide valuable insights into the field of granular convection.

Towards a more detailed understanding of granular convection under these conditions, further research could also benefit from improved visual observation tools such as computer vision and machine learning. Three dimensional snapshots, or live cross-sections of the midsole would also be particularly helpful in observing and understanding the interaction of granular convection with the flexible container. As the design of the particles becomes more specific, being able to isolate topological conditions that affect the rate of granular convection would also not be possible without these tools. Possible candidates include 3D scanning, ultrasound, or X-ray CT scanning.

CONCLUSION

The research into the *Adaptive Midsole* has successfully demonstrated the potential for footwear that personalizes cushioning and support through everyday use. The midsole prototype exhibits significant advancements over conventional and current bead-based midsole technologies, leveraging granular convection and a strategic selection of particles to offer customizability that improves over time. In contrast to a tailored approach where each shoe is custom-made, this approach allows for real-time customization with a standardized assembly and manufacturing process. Over the course of approximately 20,000 strides, the process of “wearing in” not just accounts for fit, but actually improves the comfort and performance of the shoe specific to the athlete and how they use it.

We hope for this proposition to offer a paradigm shift in

footwear with regard to personalization and adaptive design. Much of the customization promised by technologies such as computerized textile fabrication or additive manufacturing tends to follow traditional paradigms of footwear tailoring, while reliable fit is often one of the greatest pain points in terms of cost and feasibility. With the Adaptive Midsole’s ability to evolve from an undifferentiated state to a customized structure, it offers a middle-ground between mass production and personalization, potentially delivering custom footwear in a unique way. With the ability to refresh the particles in the midsole, there are also opportunities for a more sustainable shoe. Rather than throwing the shoe out when the midsole or outsole loses effectiveness, one could upgrade and prolong the useful life of the shoe. The beads might be replaced to offer a refresh of performance, or the entire midsole removed to be fully recycled. Similarly, the beads could be made from recycled materials or upcycled shoes.

With regard to the larger field of research on granular convection, this experimental process confirmed the feasibility of using granular convection within the constraints of a flexible midsole. Key findings include the identification of optimal particle ratios and materials, the successful implementation of a flexible container using liquid-printed silicone, and the importance of container geometry in influencing granular convection. These results not only validate the hypothesis but also pave the way for future research into more refined designs and materials, with the potential for more complex and adaptive midsole properties. Further exploration into the specific materials, morphology, and surface treatments of particles, as well as the introduction of internal structures within the midsole, could yield even greater control over the adaptive properties of the midsole.

This research establishes a foundational understanding of the application of granular convection in footwear and opens numerous avenues for enhancing athletic performance and

comfort. With a broader lens, learnings from this Adaptive Midsole could also apply to other areas where flexible or foam structures have a need for dynamic customizability. Other prospects include sports equipment and work safety equipment, as well as medical devices for corrective and ergonomic purposes. The adaptive nature of this macro-material offers the opportunity to think and design for functionally graded materials not just in a static sense, but with a dynamic dimension (Loh et al. 2018). The goal is to create materials and assemblies that are easily produced en masse in a standardized production, but with the ability to intelligently change for better performance through their application and lifecycle.

ACKNOWLEDGMENTS

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IMAGE CREDITS

All images by the authors.

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