

**Analyzing the Effects of Fluid-Integrated Outsoles on Foot Swelling**

**Grant Proposal**

Isaac Moore

Massachusetts Academy of Mathematics and Science at Worcester Polytechnic Institute

85 Prescott Street, Worcester, MA 01605

Abstract.....2

Mitigating Activity-Induced Foot Edema .....3

Section I: Introduction .....4

    Project Description.....4

    Background and Significance.....4

    Existing Solutions.....5

Section II: Specific Aims .....6

    Specific Aim 1: Optimizing Fluid Channel Design .....6

    Specific Aim 2: Assessing Foot Edema Reduction .....6

    Specific Aim 3: Evaluating Comfort and Perception .....7

    Outcome: End Goal .....7

Section III: Project Goals and Methodology .....7

    Project Goals .....7

    Methodology .....8

Section IV: Resources/Equipment .....8

    Researching Resources.....8

    Prototyping Equipment .....8

    Testing Equipment .....9

    Testing Logistics.....9

Section V: Ethical Considerations .....9

    Safety Criteria .....9

    Human Data and Privacy .....9

Section VI: Timeline .....9

Section VII: References ..... 10

**Abstract**

Foot swelling, or edema, is a common physiological response to strenuous or prolonged physical activities. The swelling is caused by excess fluids from the body accumulating in the feet, leading to discomfort, reduced stability, and an increased risk of injury. Individuals with reduced vascular efficiency, such as older adults, people with obesity, or those with circulatory challenges, are especially prone to the risks of foot edema, making daily activities challenging and potentially dangerous. To address this problem, this project assesses how integrating fluid channels into the outsoles of everyday shoes can reduce activity-induced foot edema by redistributing the pressure along the plantar surface of the foot. A prototype fluid-integrated shoe will be developed and tested across four activities: standing, walking, jogging, and sprinting. From each of these tests, foot edema will be measured using the water displacement method, and subjective thoughts will be considered through a participant survey. The results from the fluid-integrated shoes will then be compared to the results of standard footwear from the same tests to evaluate the difference in foot swelling and perception. The aim of this research is to evaluate whether the integration of fluids into the outsoles of shoes can mitigate foot edema-related discomfort and improve user comfort during physical activity. Findings from this study may inform future footwear design to improve safety, reduce pain, and support individuals who are prone to lower-extremity swelling.

*Keywords:* Foot Swelling, Pressure Relief, Fluid Channels, Shoe, Outsole, Fluid Integration, Edema

### **Mitigating Activity-Induced Foot Edema**

Physical activities, especially strenuous or drawn-out ones, can cause a buildup of fluid in the lower extremities that causes the afflicted region to swell up, which is called activity-induced edema (Lin et al., 2012). This swelling can lead to pain, reduced range of mobility, impaired balance, and a greater risk of injury, particularly for individuals who are prone to circulatory issues (Besharat et al., 2021).

#### **Project Description**

The primary objective of this project is to design a device that incorporates fluids into the outsoles of shoes and determine how the device can affect activity-induced foot edema. While wearing shoes with fluid-integrated outsoles, participants will engage in standing, walking, jogging, and sprinting activities for predefined amounts of time. The comfort and effectiveness of the shoes will be evaluated by measuring the foot edema caused by the activity using the water displacement method (King, 1993) and asking subjective questions to the participants after the activity. The results of the test will then be compared to the results of similar tests using standard shoes to determine whether the integration of fluids into the outsoles of shoes can reduce foot edema and improve comfort in various activities.

#### **Background and Significance**

While mild foot edema is commonly observed among most individuals, severe occurrences are typically seen among people who have decreased vascular efficiency within their bodies, such as people who are older, overweight, or have circulatory problems (Cloughley & Mawdsley, 1995). In the United States, this statistic is a particularly concerning issue because the rising obesity rates are shown to be closely related to foot edema (Burian et al., 2024). One study shows that approximately 80% of individuals with obesity suffer from some form of edema, ranging from mild, harmless swelling to chronic foot edema, which means their swelling is long-term rather than temporary (Keast et al., 2014). As a result of long-term edema, people who suffer from obesity are more prone to injuries and discomfort from everyday activities such as standing and walking. These negative effects highlight the need for strategies to mitigate foot edema.

#### ***Plantar Pressure***

Plantar pressure is the amount and distribution of force exerted on the bottom of the foot at any given time. It is commonly uneven, with the highest pressure typically occurring under the heel and the ball of the foot.

## Analyzing the Effects of Fluid-Integrated Outsoles on Foot Swelling

Moore 5

Figure 1: This figure shows a heat map of the foot on the left, with warmer colors such as red, orange, and yellow representing areas of high pressure, and cooler colors such as blue and dark green representing areas of low pressure (Galica et al., 2013).

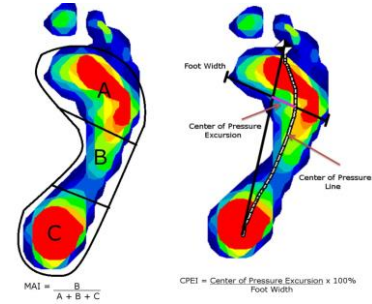


Figure 1 highlights the uneven distribution of plantar pressure across feet, with concentrated forces occurring in the same areas where the most injuries tend to occur (Nesteroviča et al., 2021). These areas under high pressure are more susceptible to a variety of injuries due to the stress put on them. This identification of high-stress areas directly impacts the design and positions of the fluid channels within the fluid-integrated outsole design, as strategically placed channels can redistribute the high-pressure areas across the feet. By doing this, the design can potentially reduce swelling and injury risk while improving comfort.

### ***Mechanical Factors***

Mechanical factors play a primary role in the development of foot edema during physical activities. One of the most documented and well-addressed mechanical causes of swelling is over-tightness in the shoelaces, which can limit blood flow to the foot and reduce lymphatic drainage (Tang et al., 2023). Suboptimal heel heights that do not align with a person's gait and the type of surface used during activities can also influence pressure distribution when they walk and contribute to swelling (Zhao et al., 2024b). In this project, fluid-integrated soles are implemented to counteract these mechanical factors by redistributing pressure within the shoe, potentially reducing foot edema and improving comfort.

### ***Environmental Factors***

In addition to mechanical causes, there are also many environmental factors that amplify the effect of foot edema. Heat is one of the primary environmental factors that affects swelling. Heat increases perspiration, skin moisture, and blister risk, while also widening blood vessels, which can affect fluid pooling throughout the body (Dessing, 2014). Ideally, by optimizing the location of fluid channels within the outsoles of shoes, the heat dissipation of the shoe would increase, which would mean heat would be further regulated throughout the shoe, so the foot is less likely to swell. Similarly, during testing, heat can have a profound impact on the data collected, so to retrieve accurate and consistent data, it is important to control the temperature differences between tests.

### **Existing Solutions**

Currently, there are many existing solutions to activity-induced foot edema; however, they all seem to have some flaws or limitations. The most common limitation among all solutions is that they simply monitor the swelling of the foot rather than mitigating the swelling as a whole. On the contrary, devices that do seem to mitigate edema in the moment, such as compression socks or external wraps on the knee or other joints, only offer temporary relief and have limited effectiveness once an activity becomes prolonged or more intense.

One example used to track foot edema is to use pressure sensors inside the insoles of shoes (Wang et al., 2025). By tracking the pressure on the insole during a physical activity, the user can monitor areas of increased stress as well as track how much the pressure increases as the activity continues, thus finding out how much the foot has swollen. This method allows researchers to acquire data in real time, as opposed to a scheduled experiment.

Figure 2 shows the prototyped design for implementing a sensor system into the insole of the user's shoe. This design has 22 sensors placed inside the insole of the shoe to collect the pressure distribution data (Wang et al., 2025).



The design I propose focuses on incorporating fluids into the outsoles of shoes to actively reduce activity-induced swelling. Unlike pressure sensing, which only monitors swelling and compression socks that provide temporary relief, fluid-integrated soles aim to redistribute the pressure when the foot strikes the ground. On top of actively reducing foot edema by redistributing the pressure of the foot into areas of need, integrating fluids into the outsoles of shoes also decreases the risk of injury to the user.

## Section II: Specific Aims

### Specific Aim 1: Optimizing Fluid Channel Design

The objective of optimizing fluid channel design is to design fluid-filled channels within a standard shoe outsole to redistribute plantar pressure more evenly across the foot during activity.

### *Approach*

The approach involves using CAD modeling and fluid dynamics simulations to model different channel configurations and placements across the outsole of the shoe. Plantar pressure will be modelled using published plantar pressure maps and simulated across the different pressures to assess the configurations during standing, walking, jogging, and running (Galica et al., 2013b).

***Justification***

Redistributing pressure along the foot would reduce the fluid buildup, which as shown in previous studies, can be done by modifying the sole of a shoe (Paton et al., 2016).

***Expected Outcome***

The expected outcome of optimizing fluid channels in the outsole is that it will significantly reduce the pressure in areas of the foot that are affected by the highest forces, such as the heel and the ball. This redistribution of forces is expected to reduce foot edema and improve comfort.

**Specific Aim 2: Assessing Foot Edema Reduction**

The objective of assessing foot edema reduction is to evaluate whether fluid-integrated shoes reduce foot edema when compared to standard shoes by using quantitative data from statistical testing.

***Approach***

Participants will perform standardized activities wearing both fluid-integrated shoes and standard shoes. Foot volume will be measured before and after using the water displacement method (King, 1993). Then, after the testing, a statistical analysis will be conducted to determine how statistically significant the change is by using either an ANOVA test or a 2-Sample T Test.

***Justification***

After a prototype is made, it is important to assess if the design has met its criteria, and the best way to do this is to compare it to normal shoes. As such, to fully conduct the study, a direct comparison must be made between the fluid-integrated shoes and standard shoes, so conclusions can be drawn about the effects on foot edema.

***Expected Outcome***

Due to the redistribution and evening out of plantar pressure, the expected outcome is that there will be a statistically significant reduction in foot swelling when using fluid-integrated shoes compared to standard shoes.

**Specific Aim 3: Evaluating Comfort and Perception**

The objective of evaluating comfort and perception is to evaluate the subjective comfort, stability, and effectiveness of fluid-integrated shoes when compared to standard shoes.

***Approach***

Following each activity, participants will complete a survey to assess comfort, stability, and effectiveness on a subjective 1 to 10 scale. Survey data will be analyzed then analyzed statistically to determine any significant differences between the shoes.

***Justification***

Even if foot edema is reduced, participants will still be reluctant to wear the novel shoe design if it is uncomfortable. For this reason, it is necessary to produce data based on subjectivity to assist in assessing the overall preference between fluid-integrated shoes and normal shoes.

***Expected Outcome***

The expected outcome is for participants to identify the fluid-integrated shoes as similar in comfort and stability during shorter sessions, but to rate them better compared to the standard shoes during longer sessions. As for the perceived effectiveness, the expected outcome is for the fluid-integrated shoe to be perceived as higher in both short and long session activities.

**Outcome: End Goal**

The ideal outcome of this work is to develop a prototype that optimizes the location and design of fluid-filled channels to reduce foot edema for the user. Successfully achieving this outcome would not only provide a new approach to mitigating activity-induced swelling but also set the stage for future research and innovation in footwear design for vulnerable populations. By demonstrating meaningful improvements in comfort, safety, and usability, this project has the potential to contribute to the creation of more accessible and health-conscious footwear options for a wider range of individuals.

**Section III: Project Goals and Methodology**

**Project Goals**

The engineering goal of this project is to design a product that incorporates fluids into the outsoles of shoes to reduce activity-induced foot edema. The engineering side of the project will be focused on the fluid channels within the outsoles, determining their optimal locations for pressure distribution and comfort.

***Design Objectives***

To develop a shoe outsole with optimally placed fluid-filled channels that redistribute plantar pressure across the foot to minimize activity-induced foot edema. The project will focus on optimizing the location and design of the channels to maximize the user's comfort during physical activities such as standing, walking, jogging, or sprinting.

***Design Criteria***

The shoe outsole must incorporate fluid channels that effectively redistribute the pressure to reduce foot edema. The design should also remain cost-effective and be made from easily attainable materials. The design should not impede any of the user's movements and should be comfortable relative to normal shoes.

***Design Constraints***

The fluid channels must be reasonably sized and must allow for the fluid to be incorporated into them after being installed into the outsole of the shoe. The shoe design must be durable and capable of withstanding multiple physical activities without breaking or deteriorating over time.

***Success Measures***

A successful design will show a significant reduction in foot edema when compared to standard shoes using the water displacement method. Participants should also perceive the comfort, support, and satisfaction of the shoe to be either equal to or superior to the standard shoe quality.

**Methodology**

To assess the effectiveness of the design and its effects on foot edema, participants will complete eight different tests. Participants will begin by measuring their initial foot volume, to be used as a control, then they will complete tests for four different activities: standing, walking, jogging, and running, wearing both the standard shoe and the fluid-integrated shoe. Each of the activities will be conducted over a predetermined duration of time to

allow for consistent data and accurate comparisons between the two shoes. Immediately after each activity, foot volume will be measured again using the same water displacement method. In addition to the objective, numerical measurements, participants will provide subjective feedback on their comfort, stability, and perceived effectiveness by answering questions on a 1-10 scale. The order of activity type and shoe type will be randomized across participants to reduce bias, and all tests will be conducted after sufficient rest has been given to achieve independence between each test.

With the data from each test, the foot edema will be determined by finding the difference between the baseline measurement and the post-activity measurement. These results will be recorded for each activity and shoe type to allow for comparisons between individual performances with the standard shoe and the fluid-integrated shoe. On top of this, the data from the questions will be compiled into datasets to be compared between the two shoe types as well. By utilizing the objective and subjective results from the testing, a statistical analysis will be conducted by using either an ANOVA test or a t-test to determine whether the fluid integration into the outsoles of shoes significantly reduces activity-induced foot edema compared to standard shoes.

#### **Section IV: Resources/Equipment**

##### **Researching Resources**

The research of this project focuses on pressure and energy transfer within the outsole of the shoe, fluid dynamics, and non-Newtonian materials. Journal articles, patent information, STL repositories, and foot biomechanic data sets will provide guidance to research into these topics. This information will assist me in developing the fluid channels within the shoe outsole and determining the ideal material to put inside the channels.

##### **Prototyping Equipment**

3D printers and CAD software will be the primary method of iteration in my project to design and produce shoes. Using CAD, STL files from open-source repositories will serve as the base for modifications to the prototyped designs. With the prototyped designs on CAD, I will be able to assess different configurations and structural designs before manufacturing a device.

##### **Testing Equipment**

SimScale will be the primary simulation software used to evaluate impact and fluid behaviors within the shoes; however, other CFD/FEA simulations may be used as well. Pressure sensors will be used after a manufactured design to validate the simulations, and computers will then be used to analyze the data.

**Testing Logistics**

STL models are imported into the simulation, where fluid channels are designed and modified with different fluid properties, and then impact forces are applied to assess the pressure distribution, energy absorption, and deformation of the shoes. This data will then be compared to typical insoles running on the same software with the same impact forces applied to assess the change.

**Section V: Ethical Considerations**

|                  |   |   |  |  |
|------------------|---|---|--|--|
| Safety Criteria  | All tests will be done under the supervision of a volunteer who is CPR/AED and First Aid certified by the American Red Cross. | Participants’ physical health will be consistently monitored.   | If any severe discomfort or pain is felt during the exercise, the participant will be immediately removed from the test. | All injuries or observations will be carefully recorded.                                 |
| Data and Privacy | Foot swelling measurements and survey responses will be collected safely and in a controlled manner.                          | Participants will be assigned unique numbers to de-identify their data; no personal identifying information will be recorded. | Participants will provide informed consent before testing and can withdraw at any time.                                  | Survey questions will focus only on comfort, perceived swelling, and shoe effectiveness. |

**Section VI: Timeline**

|                  |            |                      |                 |                 |              |               |              |
|------------------|------------|----------------------|-----------------|-----------------|--------------|---------------|--------------|
| Initial Research | Simulation | Design and Prototype | Test Setup/Prep | Data Collection | Data Cleanup | Data Analysis | Deliverables |
| 4 Weeks          | 2 Weeks    | 1 Week               | 3 Weeks         | 4 Weeks         | 1 Week       | 2 Weeks       | 2 Weeks      |



## Section VII: References

- Besharat, S., Grol-Prokopczyk, H., Gao, S., Feng, C., Akwaa, F., & Gewandter, J. S. (2021c). Peripheral edema: A common and persistent health problem for older Americans. *PLoS ONE*, 16(12), e0260742. <https://doi.org/10.1371/journal.pone.0260742>
- Burian, E. A., Rungby, J., Karlsmark, T., Nørregaard, S., Cestari, M., Franks, P. J., & Moffatt, C. J. (2024). The impact of obesity on chronic oedema/lymphoedema of the leg – an international multicenter cross-sectional study (LIMPRINT). *International Journal of Obesity*, 48(9), 1238–1247. <https://doi.org/10.1038/s41366-024-01544-0>
- Cloughley, W. B., & Mawdsley, R. H. (1995). Effect of Running on Volume of the Foot and Ankle. *Journal of Orthopaedic and Sports Physical Therapy*, 22(4), 151–154. <https://doi.org/10.2519/jospt.1995.22.4.151>
- Dessing, O., Jansen, A. J., Leihitu, C., & Overhage, D. (2014b). Experimental Study of Heat Dissipation in Indoor Sports Shoes. *Procedia Engineering*, 72, 575–580. <https://doi.org/10.1016/j.proeng.2014.06.099>
- Galica, A. M., Hagedorn, T. J., Dufour, A. B., Riskowski, J. L., Hillstrom, H. J., Casey, V. A., & Hannan, M. T. (2013). Hallux valgus and plantar pressure loading: the Framingham foot study. *Journal of Foot and Ankle Research*, 6(1), 42. <https://doi.org/10.1186/1757-1146-6-42>
- Keast, D. H., Despatis, M., Allen, J. O., & Brassard, A. (2014). Chronic Oedema/Lymphoedema: Under-recognised and under-treated. *International Wound Journal*, 12(3), 328–333. <https://doi.org/10.1111/iwj.12224>
- King, T. I. (1993). The Effect of Water Temperature on Hand Volume during Volumetric Measurement Using the Water Displacement Method. *Journal of Hand Therapy*, 6(3), 202–204. [https://doi.org/10.1016/s0894-1130\(12\)80133-5](https://doi.org/10.1016/s0894-1130(12)80133-5)
- Lin, Y., Chen, C., & Cho, M. (2012). Influence of shoe/floor conditions on lower leg circumference and subjective discomfort during prolonged standing. *Applied Ergonomics*, 43(5), 965–970. <https://doi.org/10.1016/j.apergo.2012.01.006>
- Ņesteroviča, D., Stepens, A., & Vaivads, N. (2021). Peak plantar pressure as a risk factor for lower extremity overuse injury among infantry soldiers. *Proceedings of the Latvian Academy of Sciences Section B Natural Exact and Applied Sciences*, 75(1), 52–57. <https://doi.org/10.2478/prolas-2021-0009>

Paton, J., Glasser, S., Collings, R., & Marsden, J. (2016). Getting the right balance: Insole design alters static balance in people with diabetic neuropathy. *Foot and Ankle Surgery*, 22(2), 65–66.

<https://doi.org/10.1016/j.fas.2016.05.163>

Tang, Y., Guo, X., Zhou, T., Li, L., Gao, J., Wang, Y., Huang, L., & Wei, S. (2023). Effects of shoelace tightness on lower limb biomechanics and subjective perception during lateral shuffle in basketball. *Acta of*

*Bioengineering and Biomechanics*, 25(4). <https://doi.org/10.37190/abb-02400-2024-02>

Wang, Q., Guan, H., Wang, C., Lei, P., Sheng, H., Bi, H., Hu, J., Guo, C., Mao, Y., Yuan, J., Shao, M., Jin, Z., Li, J., & Lan, W. (2025). A wireless, self-powered smart insole for gait monitoring and recognition via nonlinear synergistic pressure sensing. *Science Advances*, 11(16). <https://doi.org/10.1126/sciadv.adu1598>

Zhao, Y., Yan, S., Wang, W., Sun, B., Shi, B., & Yang, L. (2024). Influence of outsole structures on foot loading and GaT stability. *Journal of the American Leather Chemists Association*, 119(10), 438–447.

<https://doi.org/10.34314/wm9rqm56>