Analyzing Auxetic Cellular Structures for Personal Protective Gear Designs

Reem Emerson and Jongeun Rhee, University of Wisconsin-Stout, USA

Keywords: Auxetic, metamaterial, protection, body

Each year, an estimated 3.5 million youth under the age of 15 years old receive medical care for sport related injuries in the U. S. ("Sports Injury", 2019). The two-thirds of those injuries require care in emergency units and around 300,000 involve head traumas or concussions (Merkel, 2013). Between 70 to 80 percent of adolescents with an age of fifteen drop out of sports. One of the main reasons for adolescents' sport drop-out is the occurrence of injuries (Habelt et al., 2011). In addition, the incidence of sports injuries comes at a high cost in economic terms ("Sports", 2022). The estimated annual cost derived from sports injury management amounts to two billion dollars in the U. S. healthcare system (Merkel, 2013). Under these circumstances, it is critical to design athletic gears to prevent injuries, protect young athletes' health, and increase safety in sports. Reducing the risk of suffering injuries will promote adolescents' lifetime participation in sports and improve public health.

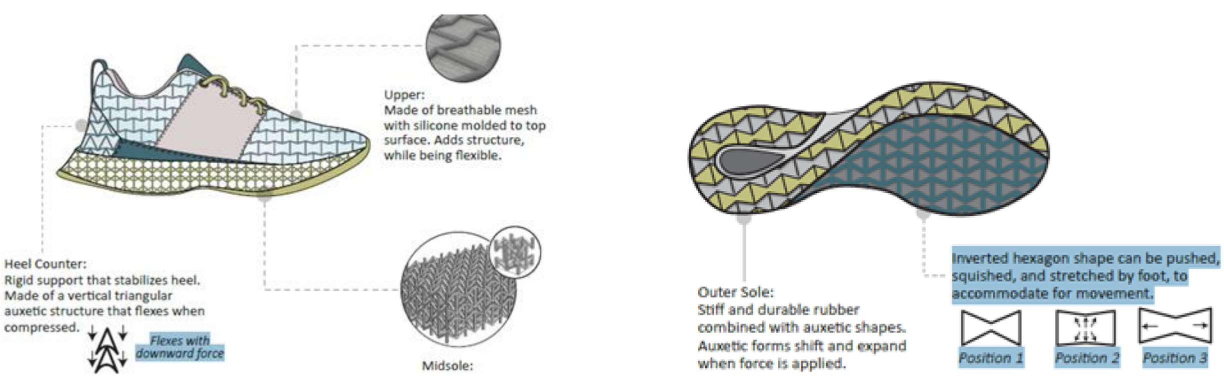
The primary objective of this study is to create a new athlete shoe design utilizing auxetic cellular structures. The secondary objective is to analyze the properties of various auxetic cellular structures for a wearer's body protection from impacts. Through the exploration of auxetic cellular structures and their application to personal protective equipment (PPE) including sports apparel and accessories, the outcomes of this study will contribute to create designs that prevent or reduce injuries caused by forceful impact.

Auxetics are material structures that have a negative Poisson's Ratio (Hu, Zhang, & Liu, 2019). The Poisson's ratio is the ratio of transverse contraction strain to longitudinal extension strain in the direction of stretching force (Greaves, et al., 2011). When stretched, a cellular structure becomes thicker in the two directions perpendicular to the applied tension. When compressed, it becomes thinner in the two directions perpendicular to the applied compression. Tensile deformation is considered negative. Compared to conventional material structures, auxetic structures have significantly higher energy absorption, fracture resistance, shear resistance, and impact resistance (Kelkar et al., 2020). The auxetic structures are categorized into re-entrant structures, chiral structures, rotational rigid structures, and other miscellaneous structures, such as origami structures (Hu, Zhang, & Liu, 2019). Each type has difference geometric structures and deformation mechanisms. To meet the research objectives, the various cellular auxetic mechanical structures are explored and evaluated using ASTM D 5034 Grab Test method. Three aspects of auxetic materials are explored to optimize both protective properties of athletic shoe designs: Laser cut, woven, or injection molded forms for upper side of shoe; micro level cellular structure foam for insole; and thermoplastic polyurethane (TPU) auxetic forms for the shoe base.

The upper side of our new running shoe design is made of breathable mesh with silicone molded to top surface that adds structure, while being flexible (See Figure 1.). The midsole consists of a lattice auxetic structure (i.e., a type of re-entrant structure), which provides the even bed of support, while giving bounce-back and cushion to impacted areas. The heel counter is made of rigid support of a vertical triangular auxetic structure that flexes when compressed. As a result, it effectively stabilizes heel. The outer sole comprises stiff and durable rubber combined with an inverted hexagon shape of auxetics. This specific re-entrant structure is selected for the outer sole forms as they shift and expand when force is applied. The inverted hexagon auxetic structures effectively accommodate wearers' movement as they can be pushed, squished, and stretched by foot.

Traditional running shoes have an outsole made of carbon rubber and an upper made of knit polyester or nylon mesh. Switching from traditional athletic shoe materials and designs to incorporate auxetic foams and structures poses many benefits. Shock absorbing auxetic structures combined with foam and rubber help reduce repeated stress and prevent injuries related to pressure points. The new shoe design structures are designed to withstand high stress on a molecular level. The result of this study demonstrates that auxetic materials have many advantages over traditional materials in the application of sports related personal protection equipment. Auxetic foams are more shock absorbing, lightweight, flexible, forms to the body, and have more tensile strength as compared to traditional open and closed cell foams. This opens the doors to countless possibilities where auxetic foams, structures, and knits could be applied. Auxetics could be a paramount asset in reducing sports injuries. Examples of potential designs include helmets to prevent traumatic brain trauma, cycling gear, protective elbow and knee pads, and so many more applications in an effort to reduce injuries.

Figure 1. New Athletic Shoe Design



References

Greaves, G. N., Greer, A. L., Lakes, R. S., & Rouxel, T. (2011). Poisson's ratio and modern materials. *Nature Mater 10*, 823–837. https://doi.org/10.1038/nmat3134

Habelt S., Hasler C. C., Steinbrück K., & Majewski M. (2011). Sport injuries in adolescents. Orthopedic Reviews, 3(18), 82-86. https://doi.org/10.4081/or.2011.e18

Hu, H., Zhang, M., & Liu, Y. (2019). *Auxetic textiles*. Woodhead Publishing, an imprint of Elsevier. https://doi.org/10.1016/C2016-0-04399-1

Kelkar, P. U., Kim, H. S., Cho, K.-H., Kwak, J. Y., Kang, C.-Y., & Song, H.-C. (2020). Cellular auxetic structures for mechanical metamaterials: A Review. *Sensors*, *20*(11), 1-26. https://doi.org/10.3390/s20113132

Merkel D. L. (2013). Youth sport: positive and negative impact on young athletes. *Journal of Sports Medicine*, *4*, 151-160. https://doi.org/10.2147/OAJSM.S33556

"Sports and recreational injuries" (2022, July 8). Injury Facts. https://injuryfacts.nsc.org/home-and-community/safety-topics/sports-and-recreational-injuries/

"Sports injury statistics". JHM. (2019, November 19). https://www.hopkinsmedicine.org/health/conditions-and-diseases/sports-injuries/sports-injury-statistics