Available online at www.IJournalSE.org

Italian Journal of Science & Engineering

Vol. 1, No. 3, October, 2017

Development of a Biomedical Neckbrace through Tailored Auxetic Shapes

Martina Panico [a], Carla Langella [a*], Carlo Santulli [b]

[a] *Università degli Studi della Campania, Dept. of Civil Engineering, Design and Built Environment, via Roma 29, 81031 Aversa, Italy*

[b] *Università degli Studi di Camerino, School of Achitecture and Design, viale della Rimembranza, 63100 Ascoli Piceno, Italy*

Abstract

Objectives

This work concerned the study of auxetic materials are cellular structures with negative Poisson's ratio, therefore bending, instead of stretching, when pulled, therefore offering support.

Methods/Analysis

Nature is able to develop irregular cellular structures, making them denser only when needed and sparser in other areas and this experience has been applied to the development of structure with auxetic geometries other than the classical bow-shaped one.

Findings

The study of these inherent characteristics of nature allowed the development of three innovative auxetic patterns, not existing in literature, modifying their structure to optimize their function, starting from the study of elementary geometrical shapes to arrive to auxetic unitary cells formed by concave polygons, united to other geometrical elements so to obtain auxetic structures both of multicellular type and of node-link type.

Novelty/Improvement

The knowledge acquired about novel auxetic structures has been applied to the development of an innovative neckbrace for orthopaedic purposes, which is comfortable, in that it is flexible, resistant, anatomical and transpiring.

Keywords:

Auxetic;
Poisson's Ratio;
Neckbrace;
Koch's Curve;
Bio-inspiration.

Article History:

Received: 04 October 2017

Accepted: 05 November 2017

1- Introduction

When pulled, most materials do gradually reduce their section as the effect of plastic deformation leading to "necking": this is defined as having a "Newtonian" behaviour. In mathematical terms, this is expressed by showing a positive value of the Poisson's ratio, defined as the ratio between transverse and longitudinal deformation. Poisson's ratio is normally positive, because inter-atomic bonds do usually realign with deformation [1]. In some cases though, particularly related to cellular materials, wherever cells have re-entrant shapes, Poisson's ratio value is negative, which leads to the consequence that materials when pulled along their length become thicker in one or more other directions [2]. The behaviour of Newtonian and auxetic materials is compared in Figure 1.

* **CONTACT**: Carlo.santulli@unicam.it

DOI: http://dx.doi.org/10.28991/ijse-01113

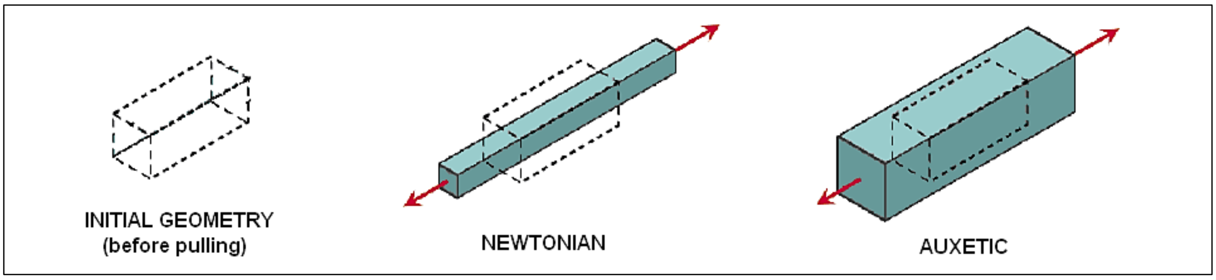

Figure 1. Compared tensile behaviour of Newtonian and auxetic material

Auxetic materials do exist in nature, in particular in membranous structures, as in the skin of some reptiles, such as salamander [3], in cow teat [4] or in cat skin [5]: in this sense, it is very suggestive to note that this characteristic allows animals carrying out abrupt movements without their skin tearing off. The prospected fields of application derive from a series of enhanced properties of the auxetics, which include indentation resistance, hence improving energy absorption, fracture toughness, porosity variation and better ability to be anchored when inserted into a surrounding material, to which the auxetic tends to be "locked in". Also, in case it is subjected to pure bending loading, the auxetic material tend to show a dome-like curvature, as opposed to the saddle-shape of a Newtonian one, which in practice may lead to increased de-fouling properties [6]. As from above, it is clear that these characteristics may be of interest for the development of design objects: some examples of prospective application have previously explored and presented for items where safety appeared to be a requirement of paramount importance, such as for example in seat belts [7]. Another example is the proposed use of auxetic honeycomb structures to produce helmets or protective equipments against sudden collisions [8]. In design terms, the auxetic properties would need to be "exploited" to be translated in a successful emotional interaction of user with the product, which is widely recognised more recently as a practice leading to improved sustainability [9-10]. To achieve this, it is important to start from design by performing a significant number of experiments in order to modify in a tailored way the geometrical characteristics of the auxetic structure, possibly relating them with the user experience. In biomedical terms, this would possibly allow designing customized devices for the patient, personalising the structure according to the pain map and body morphologies.

In practical terms, to attempt to produce auxetic structures behaving in different ways and flexibly adapting to loading, a kind of geometrical optimisation process needs to take place, which needs applying concepts of fractal geometry then fabricating simple cardboard based models, a method which has been used to compare their properties to traditional honeycomb [11]. This will subsequently lead to better adapting the structure to use and come to its fabrication by using 3D prototyping.

2- Auxetic Structures

Probably the simplest honeycomb structure that presents auxetic properties is the one with cells with re-entrant shapes, which is often defined as "bow shaped" [12] (Figure 2). Bow-shaped auxetic materials, subjected to tensile load, is deformed tending to align horizontally the diagonal sides, while in contrast diagonal sides are moved inwards in response to a compressive load therefore shrinking the structure (Figure 3). Bow-shaped auxetic cells, where the effect is linked with the presence of oblique sides, have been first introduced by Gibson in 1982. A second class of auxetic structures is formed by chiral units, which are formed by linking rectilinear structures to central nodes obtained with elementary geometries, such as squares, circles or rectangles. Types of chiral structures with Poisson's ratio of -1 have been first proposed by Prall and Lakes in 1997 [13]. More recently, also the auxetic structures with rotating cells have been proposed by Grima and Evans in 2000 [14]. Rotating cells are united among them only through their edges becoming like hinges and leaving sides free, and can expand through a rotation occurring between contact points.

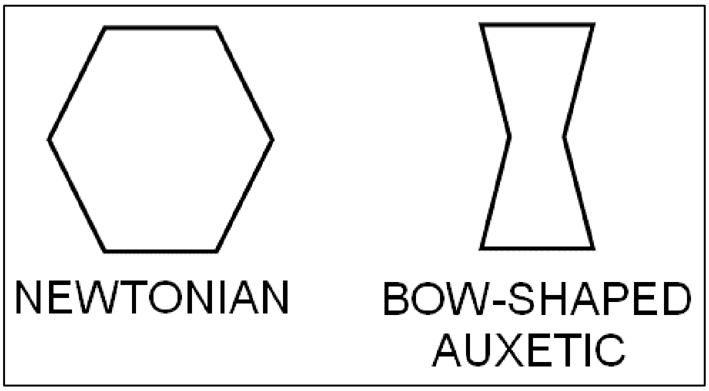

Figure 2. Newtonian and re-entrant (bow-shaped) auxetic cell geometry

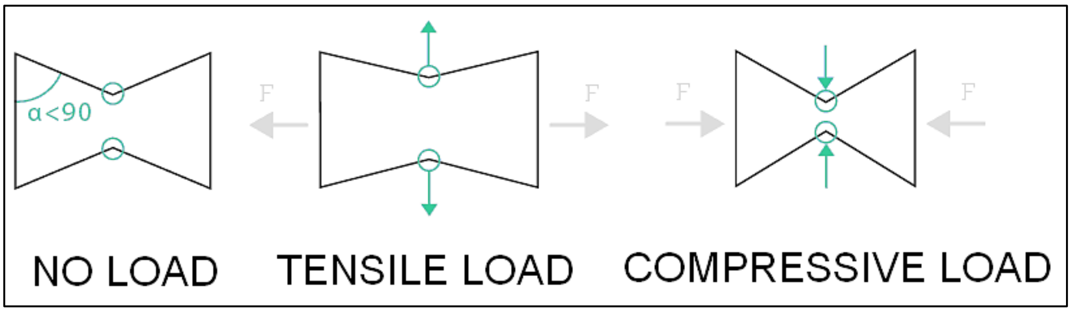

Figure 3. Re-entrant auxetic behaviour

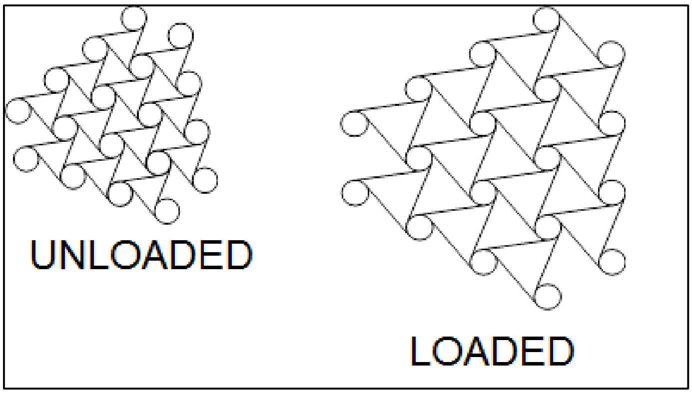

Figure 4. Chiral auxetic behaviour

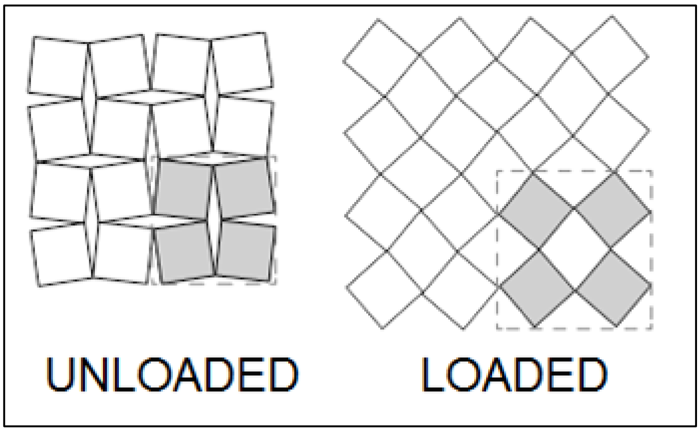

Figure 5. Rotating cell auxetic behaviour

2-1- Properties of Auxetic Structures

The characteristics of swelling and compression of auxetic structures in relation to the acting force, confer to the material special properties, and it is for this reason that they are receiving increasing attention in different sectors, from the applications for crystallization systems owed to their variable permeability [15] to applications at a bigger scale for energy and sound damping [16], for foam-filled structures in the aerospace sector [17] and for medical devices, in particular drug-eluting stents [18].

Beyond offering an enhanced tensile and compressive resistance, negative Poisson's ratio could also improve some other mechanical properties, such as for example shear modulus, vibration damping and resistance to indentation load. In particular, the auxetic material was both more difficult to indent than the other materials at low loads and showed the least plastic behaviour, which resulted in a very rapid viscoelastic creep recovery with virtually no residual deformation [19]. In other words, the auxetic material tends to flow towards the point where load is applied, which explains its improved resistance when compared with Newtonian materials.

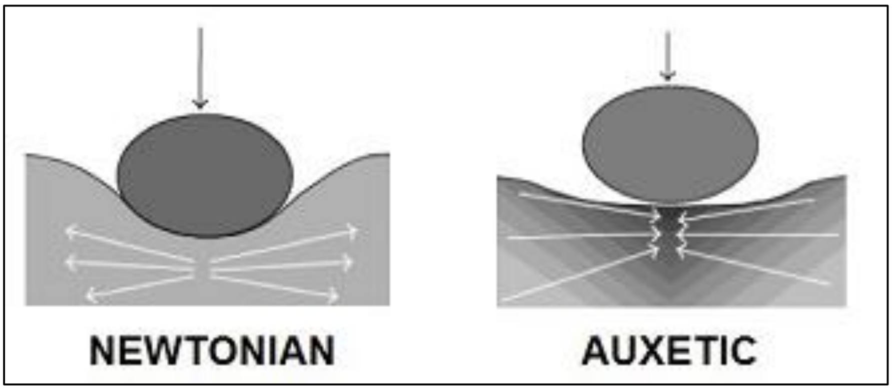

Figure 6. **Indentation behaviour of a Newtonian and auxetic material**

Their mechanical behaviour, together with their capacity of swelling when pulled, allows auxetic structures being excellent candidates for the production of fibres for composite materials, in that their properties enable improving interfacial strength by increasing the force necessary to pull-out the fibres from the matrix. They are also considered also as membrane materials for filters, capable of reducing the occlusion of pores [20]. The auxetic effect has the capacity to increase the dimension of pores when the membrane is subjected to tensile loading. In turn, increasing the dimension of the pores makes it possible to clear them from the obstructing particles without having to proceed to the substitution of the membrane, or else the substances can be released gradually, according to necessities (Figure 7).

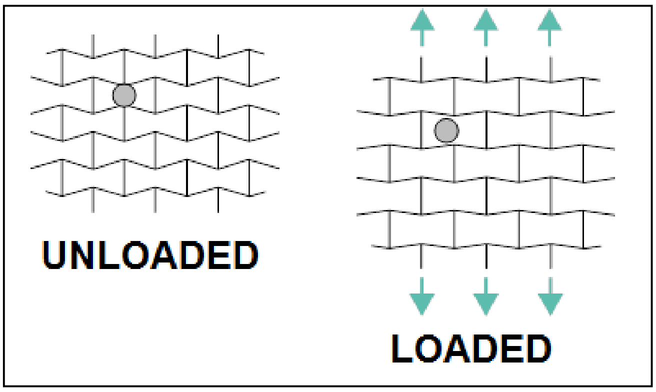

Figure 7. **Auxetic membrane**

Additionally, another property of significant industrial interest of auxetic materials is the so-called synclastic (bridge-like) curvature, which, unlike what occurs in conventional cellular structures, allows the auxetic structure adhering in an optimal way to curved or wavy surfaces and adapting to the most different shapes at different dimensional levels [21] (Figure 8).

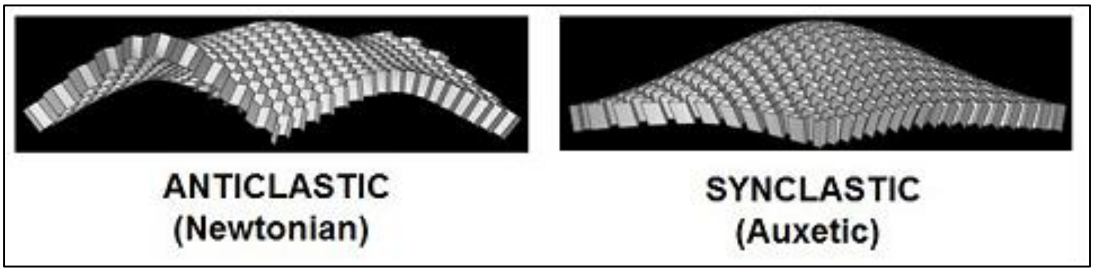

Figure 8. **Curvature of a Newtonian and of an auxetic cellular structure**

2-2- New Auxetic Structures and Structural Optimisation

It has been reported that the principal characteristic of auxetic structures is their possibility to flexibly withstand both compressive and tensile loads [22]. In other words, with respect to a positive Poisson’s ratio porous material, auxetics show enhanced porosity variation when stretched or compressed, which leads in turn to enhanced energy absorption, in terms of impact, vibration or ultrasonic. This is reflected into a similarly enhanced ‘anchorability’ through ease of insertion into a surrounding material, due to lateral contraction in response to the compressive insertion force, and resistance to removal through ‘locking in’ due to lateral expansion when placed under a tensile removal force [23]. Other characteristics of the auxetic structures, as illustrated in Figure 8, are that, if arranged to provide also a 3-D curvature effect, for example by having a chiral (node-link) or a rotating square, they are able to produce basically the same deformation pattern both from compressive and tensile loading, which in the end results in a considerable flexibility of use in different service conditions (Figure 9). It has been also considered that, passing to rotating rectangles, the angle of rotation would determine the behaviour of the structure as Newtonian or auxetic by a continuous variation of Poisson's ratio with it (Figure 10) [24].

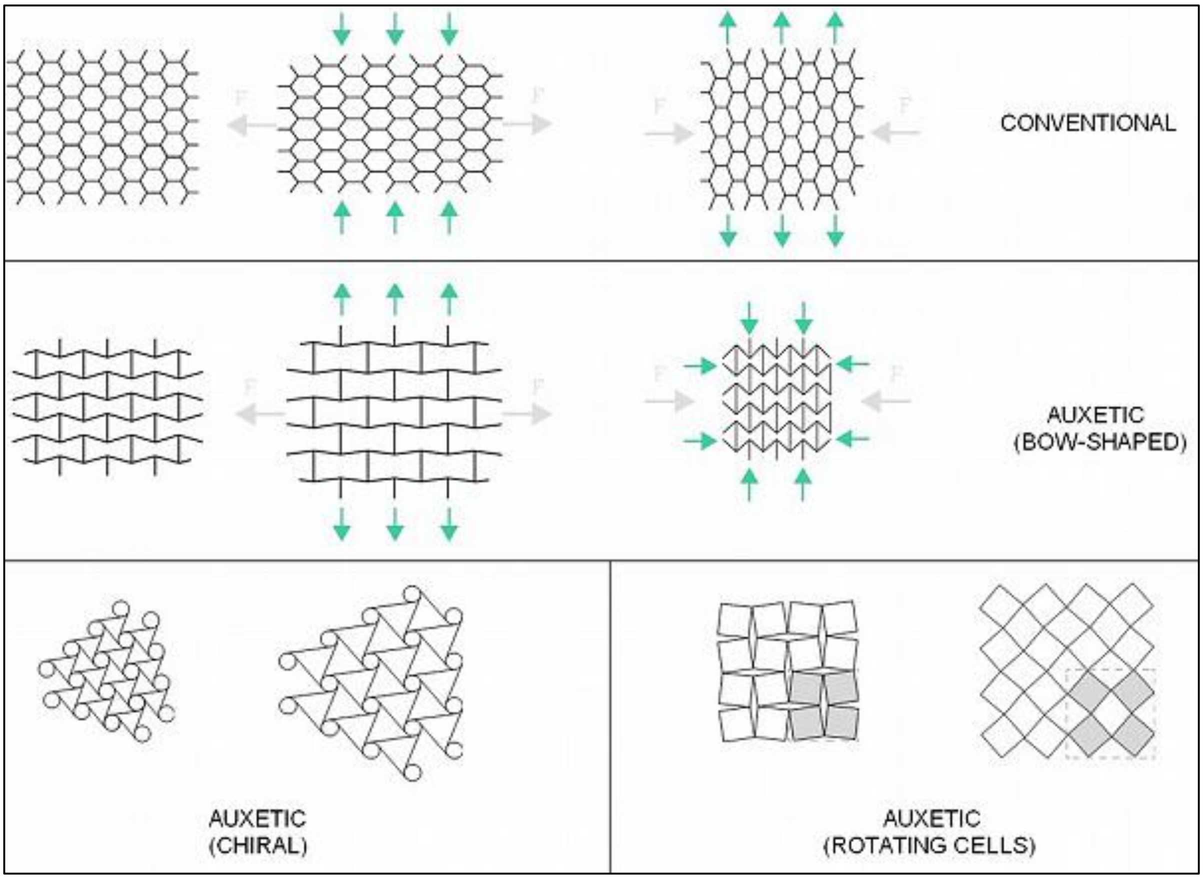

Figure 9. Deformation patterns of Newtonian and auxetic cellular structures

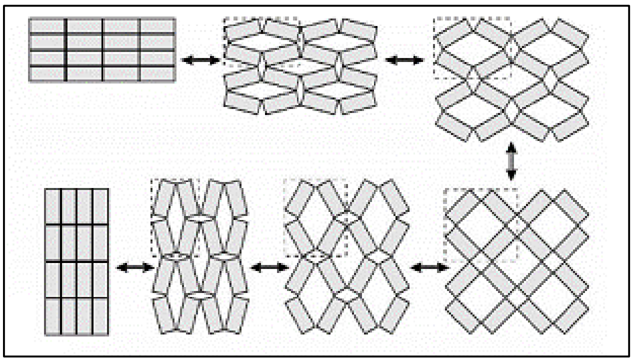

Figure 10. Newtonian or auxetic behaviour of rotating rectangles cellular structures

In nature, the creation of auxetic structures corresponds to the need to compensate for the fact that force, be it compressive or tensile, is not homogeneously applied throughout the mass of the natural object, therefore the global force obtained by summing up the one applied in all the points of the structure, requires to be frequently "shifted" of some angle. As an example, the structure modelled in form of rotating rectangles, as from Figure 10, was revealed in silicate-α-cristobalite, confirming that the rotation of rigid units is capable of generating auxetic behaviour at the molecular level [25].

In other cases, however, such as for cellulose structure, hence paper, auxetic behaviour demonstrated in out-of-plane deformation under a tensile load can depend upon the presence of strong hydrogen bonds between fibres at junction points and the interwoven, though irregular, organization of fibres [26]. A particularly interesting way of achieving auxetic behaviour is in the field of textiles, hence practically resorting to knitting procedures: the potential of negative Poisson's ratio during service has been demonstrated in terms both of size fitting ability and of protection potential for the garments [27]. In other words, what is achieved in this case is that cellular structure is optimised according to necessities, with densification only in places where this is needed. Some typical examples of this strategy are the honeycomb-like vascular bundles of *Cocos nucifera*, and the radial density of the cells distribution in *Iriartea gigantea*, providing higher bending stiffness compared with what achieved by a uniform density section [28].

2-3- Development of Innovative Auxetic Structures

A reflection, aimed at combining the above characteristics, led to the idea to develop different auxetic patterns, favouring the development of an approach that would empower the use of these structures, focusing on their possibilities, according to principles of optimisation of natural materials. The result has been the design of three new auxetic patterns, not existing in literature, which are able to modify their structure to optimise their functions. This process started from the study of elementary geometrical shapes to get to auxetic unitary cells formed by concave polygons, which were united to other geometrical elements in order to obtain auxetic structures of multicellular type built as node-link structures (construction and deformation process are given in Figures 11-13)

To realise an auxetic structure able to change and be optimised according to the required needs, an approach has been followed, similar to the one through which nature optimises its structures, therefore using a system statistically not regular or else a fractal system. The application of the latter allowed the creation of a new fractal auxetic cell. Hence, starting from the concave polygon used for the new structures, through iterative passages taken from the model of fractal Koch's curve [29], the new cell has been obtained (Figure 14). This has an effect on the type of auxetic behaviour, obtaining a hybrid between a re-entrant cells and a rotating cells structure, since the links between the smaller stars are not applied between the hinges, but through the vertices, therefore presenting a two phases reaction (Figure 15). In the first instance, with the application of a very low force, the stars closest to the direction of the acting force rotate (such as it occurs in the rotating cells auxetic structures); after this, applying a higher force, the stars allow collapsing the sides located closer to the centre of the cell, causing the swelling of the whole cell. This type of behaviour characterised by two consecutive phases enables the auxetic cell, resized after deformation, to react in a different way with respect to the primitive auxetic cell inside a whole structural pattern, which includes it. In Figures 16-18 are reported the structural variation of the designed auxetic patterns, both according to the non-regular system, built by mixing different basic geometries, and according to the fractal one, which follows Koch's curve.

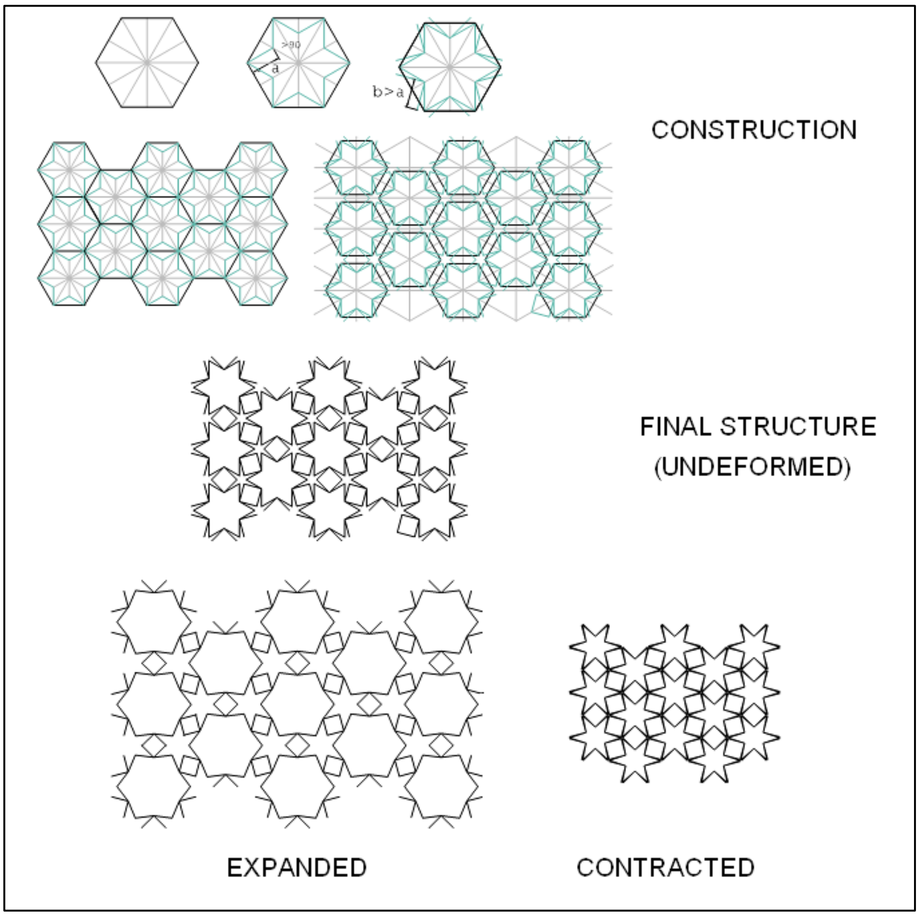

Figure 11. **Auxetic structure n.1**

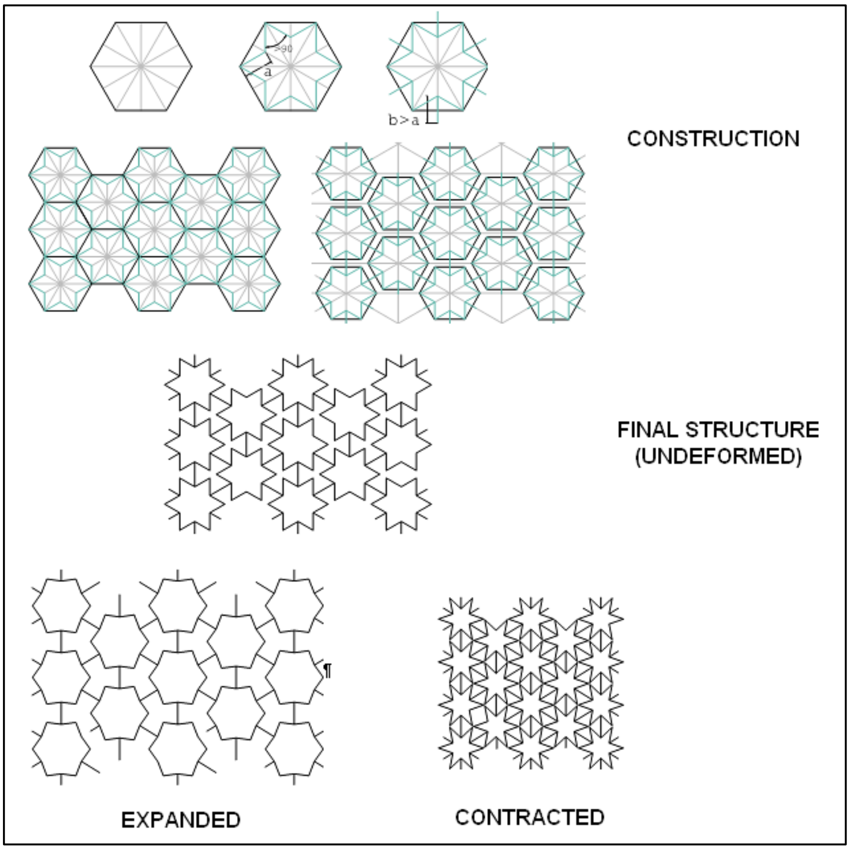

Figure 12. Auxetic structure n.2

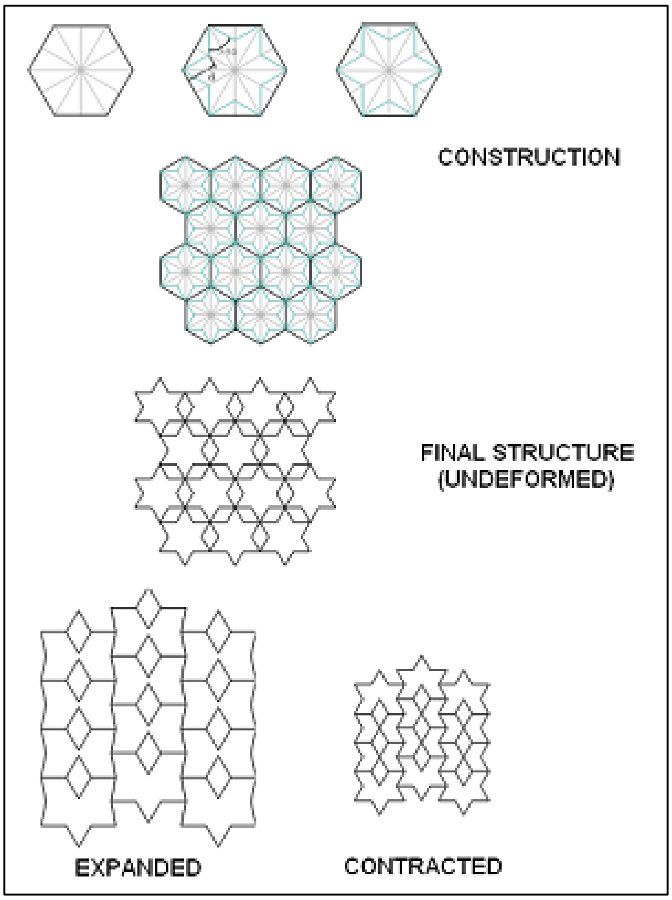

Figure 13. Auxetic structure n.3

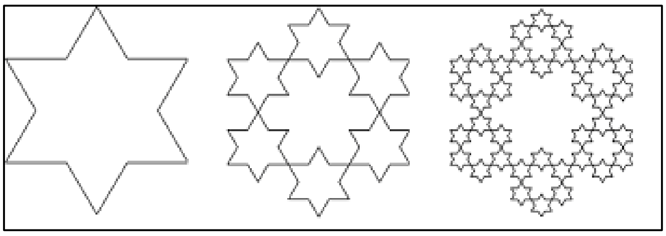

Figure 14. Construction process of the fractal auxetic cell

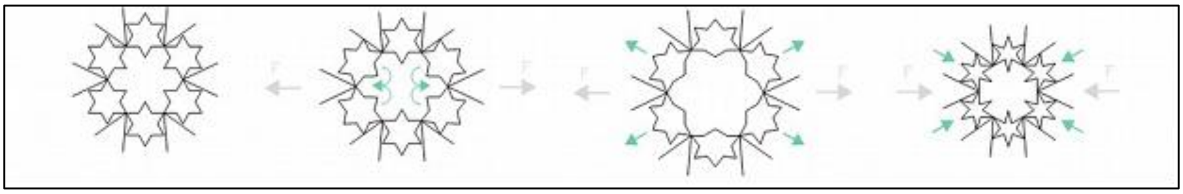

Figure 15. Process deformation of the fractal auxetic cell

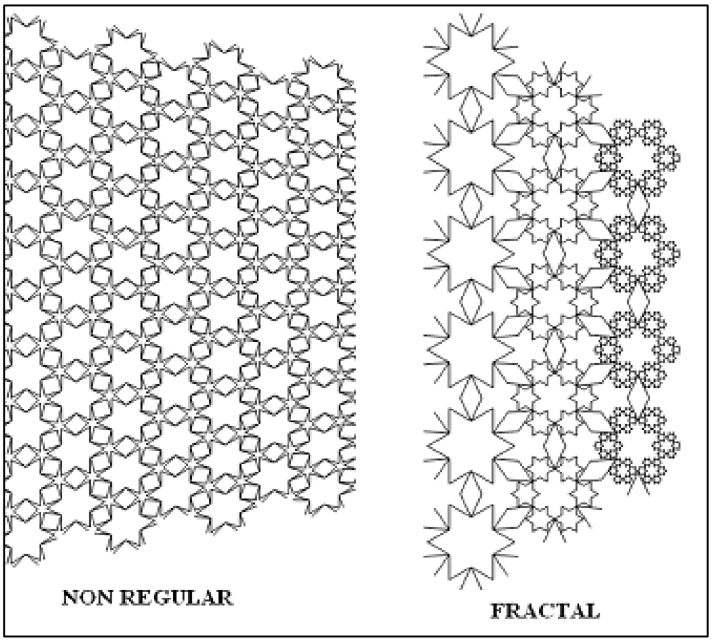

Figure 16. Dimensional variation of auxetic structure n.1 in a non-regular system or in a fractal one

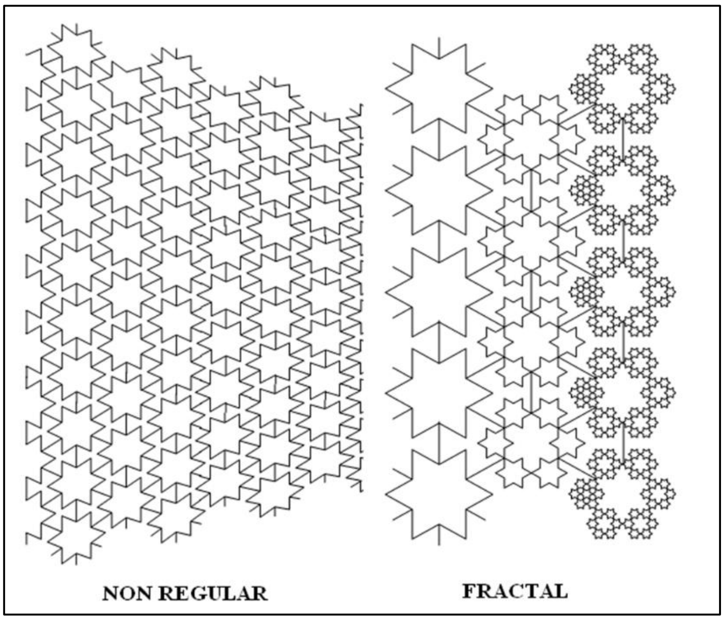

Figure 17. Dimensional variation of auxetic structure n.2 in a non-regular system or in a fractal one

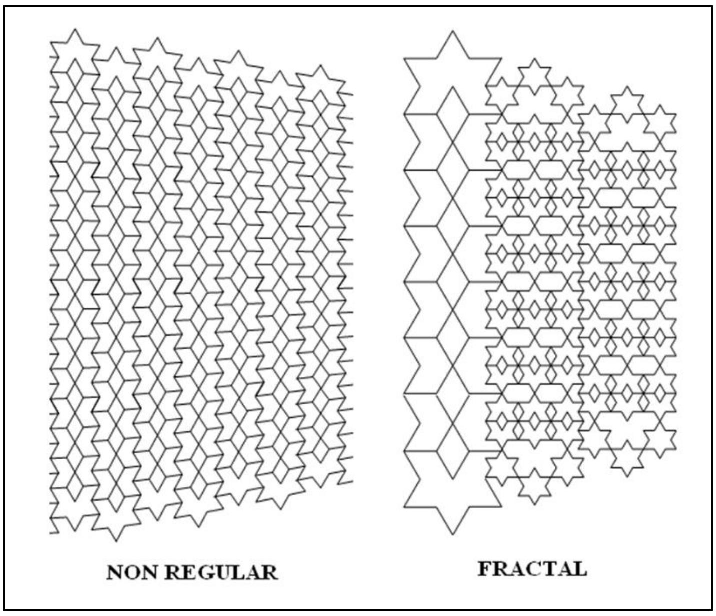

Figure 18. Dimensional variation of auxetic structure n.3 in a non-regular system or in a fractal one

3- Application: Auxetic Neckbrace

In the biomedical field, auxetic micro-porous and cellular materials showed some potential: in coronary angioplasty, a dilator for opening the cavity of an artery or other vessel has been proposed by exploiting the full lateral expansion of a flexible auxetic polymer hollow rod or sheath under tension [30]. Another possibility was created with polymeric auxetic structures having the potential to create filters with enhanced pore size and with tuneable shape [31]. This would therefore possibly overcome the problems of filter systems with conventional materials, such as reduction in filtration efficiency and development of a pressure drop across the filter in case of blockage [32]. In the case of the auxetic neckbrace, this is intended as a biomedical device external to the human body, aimed at the wellbeing of the neuromuscular system of the cervical spine, developed starting from the logic and the processes that nature employs to use and modify its materials, more specifically the resistance and structural optimisation in conformity to the physiological functions. It has a therapeutic scope for pathologies entailing non critical alterations (but whose consequences may be much more serious), and preventive, since it educates our postural behaviour in some defined situations of our daily life.

Cervical collars are the orthopaedic devices most used in the medical sector. According to epidemiological studies, cervical spine pathologies afflict a significant share of population in different moments of their life, which allows categorising this pathology amongst the most diffuse muscular-skeletal problems in the world [33]. The main causes of these pathologies are to be ascribed to inadequate functional requests that we do to our neck, which, as it is the case for the whole of our body, is designed to move, whereas in contrast our daily life may oblige ourselves to be steady, assuming wrong postures, and therefore producing muscular-skeletal suffering [34]. Moreover, a further cause is the so called "whiplash injury" that brings, immediately and overtime, cervical problems. The person using this biomedical device needs therefore having a maximal comfort, which is obtained by creating a stable and protective environment, limiting the inconveniences caused by common neckbraces, such as the loss of transpirability and freedom of movements, non-adaptability to neck morphology, difficulty to carry out some daily activities and, finally, the sensation to be "ill" or "disabled" having therefore physical, but also psychological benefits.

The use of the auxetic structure is the core innovation of the neckbrace: exploiting the intrinsic logic according to which these structures are used in nature, it is able to offer significant properties with respect to the existing products. It is resistant, flexible, it has the aspect of a "second skin" which, as it occurs in nature, is able to adapt itself to the conditions of external context, or more specifically, to neck anatomy, offering pleasurable sensations and allowing the skin transpiration thanks to its weave not covering completely the neck.

Having the function of head support, favouring therefore the mechanical discharge of muscles and the relaxation of the same, the auxetic structure guarantees especially the neck movement, which is a fundamental need for healing cervical pathologies, by contracting and expanding in response to the actions coming from the surroundings. In practice, if the neck has a deflection, inducing on one side a contraction of the muscles and on the other side their extension, the structure would at the same time contract and expand in different parts of it (Figure 19) with limited cluttering and nuisance. To offer the maximal support to the neck, the geometry of the collar would correspond to the cutaneous projection of the muscular belts interested or, in specific cases, to the "pain map" of the patient (Figure 20). In this case, the auxetic structure applied to the collar would present a structural variation aimed at optimising the functions of the product according to physiological needs, obtaining an economy of material and energy in the least interested areas. In practice, corresponding to the muscular belts that require improved support, the structure will be characterised by a denser plot that will present high resistance to external actions. In contrast, in areas in which a particular support is not required, the structure with a sparser plot is applied (Figure 21).

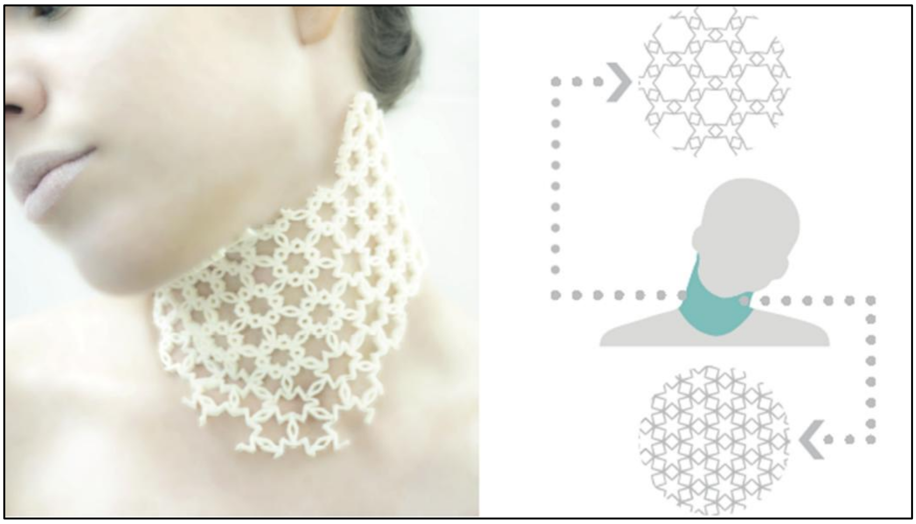

Figure 19. Adaptation of the structure to neck movements

Figure 20. Optimisation of the support shape based on functional needs

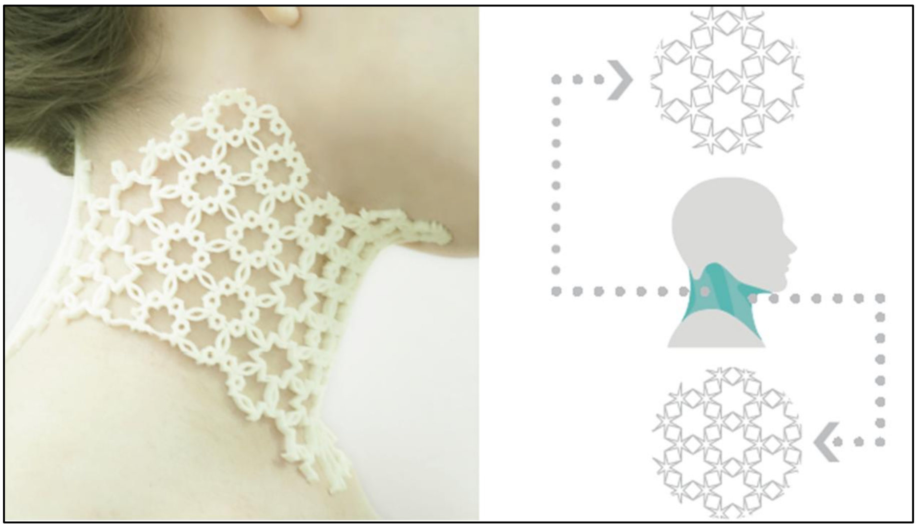

Figure 21. Optimisation of the structure based on functional needs

The geometry of the collar and the structural optimisation will be defined thanks to digital fabrication technologies, through which personalised cervical prostheses could be obtained, therefore centred on the specific clinical case: the idea is to that pain map would orient the design of the collar to satisfy the anatomical and physiological needs of the patient, offering the flexibility and the support adapted to the user's conditions (Figure 22).

Finally, the material selected for the realisation of the collar through 3D printing, a polyurethane rubber based material, Flex Skin, has been developed especially to be sure when in contact with the human skin, deprived of carcinogenic agents and that would not release chemicals in the endocrine system. The auxetic cervical collar can be described as a support adapted to all situations: it can be worn in front of the PC, during working hours, sport activities, or even during the night. The result is therefore an auxetic neckbrace that is flexible, resistant, anatomical, transpiring, personalized, but above all comfortable.

4- Conclusion

The main characteristic of auxetic structures is their resistance to tensile and compressive stresses: however, in the majority of cases, the force is not uniformly applied in the whole mass of the object, but there are critical points in which a higher force is applied, hence these differences would create a number of problems. Nature, in cases, such as for example plant stems, is able to purposely optimize its cellular structure: the idea is to make it denser only when needed and obtaining therefore a material and energy economy in other areas, resulting in an irregular cellular structure. However, little attention has been dedicated so far to this salient characteristic of nature. This has been the object of this study, fostering the development of an approach that would empower the use of these structures and would exalt them with respect to the present applications, according to the logic of optimization of natural materials. The result has been the design of three innovative auxetic patterns, not existing in literature, in order to modify their structure to optimize their function, starting from the study of elementary geometrical shapes to arrive to auxetic unitary cells formed by concave polygons, united to other geometrical elements so to obtain auxetic structures both of multicellular type and of node-link type.

Figure 22. Adaptation of the neckbrace to body movements

5- References

[1] Evans, K. E., and K. L. Alderson. "Auxetic materials: the positive side of being negative." Engineering Science & Education Journal 9, no. 4 (2000): 148-154.

[2] Alderson, K. L., A. Alderson, and K. E. Evans. "The interpretation of the strain-dependent Poisson's ratio in auxetic polyethylene." The Journal of Strain Analysis for Engineering Design 32, no. 3 (1997): 201-212.

[3] Lakes, Roderic. "Materials science: A broader view of membranes." Nature 414, no. 6863 (2001): 503-504.

[4] Lees, Caroline, Julian FV Vincent, and J. Eric Hillerton. "Poisson's ratio in skin." Bio-medical materials and engineering 1, no. 1 (1991): 19-23.

[5] Veronda, D. R., and R. A. Westmann. "Mechanical characterization of skin—finite deformations." Journal of biomechanics 3, no. 1 (1970): 111IN9123-122124.

[6] Alderson, A., J. Rasburn, K. E. Evans, and J. N. Grima. "Auxetic polymeric filters display enhanced de-fouling and pressure compensation properties." Membrane Technology 2001, no. 137 (2001): 6-8.

[7] Santulli, Carlo, and Carla Langella. "Study and development of concepts of auxetic structures in bio-inspired design." International Journal of Sustainable Design 3, no. 1 (2016): 20-37.

[8] Gaspar, Neil, X. J. Ren, Chris W. Smith, J. N. Grima, and Ken E. Evans. "Novel honeycombs with auxetic behaviour." Acta Materialia 53, no. 8 (2005): 2439-2445.

[9] Page, Tom. "Product attachment and replacement: implications for sustainable design." International Journal of Sustainable Design 2, no. 3 (2014): 265-282.

[10] Chapman, Jonathan. "Design for (emotional) durability." Design Issues 25, no. 4 (2009): 29-35.

[11] Sparavigna, Amelia Carolina. "based Metamaterials: Honeycomb and Auxetic Structures." International Journal of Sciences 3, no. 2014-11 (2014): 22-25.

[12] Gibson, Lorna J., M. F. Ashby, G. S. Schajer, and C. I. Robertson. "The mechanics of two-dimensional cellular materials." In Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, vol. 382, no. 1782, pp. 25-42. The Royal Society, 1982.

[13] Prall, D., and R. S. Lakes. "Properties of a chiral honeycomb with a Poisson's ratio of—1." International Journal of Mechanical Sciences 39, no. 3 (1997): 305-314.

[14] Grima, Joseph N., and Kenneth E. Evans. "Auxetic behavior from rotating squares." Journal of Materials Science Letters 19, no. 17 (2000): 1563-1565.

[15] Rasburn, J., P. G. Mullarkey, Ken E. Evans, A. Alderson, S. Ameer - Beg, and W. Perrie. "Auxetic structures for variable permeability systems." AIChE journal 47, no. 11 (2001): 2623-2626.

[16] Scarpa F, Ma Y, Zhang D, A nonlinear auxetic structural vibration damper with metal rubber particles, Smart Materials and Structures 22 (8), 2013, 084012.

[17] Bianchi M, Scarpa FL, Smith CW, Stiffness and energy dissipation in polyurethane auxetic foams, Journal of Materials Science 43, 2008, 5851-5860.

[18] Doll WJ, Fricke BA, Becker BR, Structural and drug diffusion models of conventional and auxetic drug-eluting stents, Journal of Medical Devices 1 (1), 2006, 47-55.

[19] Alderson KL, Fitzgerald A, Evans KE, The strain dependent indentation resilience of auxetic microporous polyethylene, Journal of Materials Science 35, 2000, 4039-4047.

[20] Aw J, Zhao H, Norbury A, Li L, Rothwell G, Ren J, Effects of Poisson's ratio on the deformation of thin membrane structures under indentation, Physica Status Solidi (b) 252 (7), 2015, 1526-1532.

[21] Sanami M, Ravirala N, Alderson K, Alderson A, Auxetic materials for sports applications, Procedia Engineering 72, 2014, 453-458.

[22] Scarpa F, Yates JR, Ciffo LG, Patsias S, Dynamic crushing of auxetic open-cell polyurethane foam, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 216 (12), 2002, 1153-1156.

[23] Liu Y, Hu H, Lam JKC, Liu S, Negative Poisson's Ratio Weft-knitted Fabrics, Textile Research Journal 80 (9), 2010, 856-863.

[24] Grima JN, Alderson A, Evans KE, Negative Poisson's ratios from rotating rectangles, Computational Methods in Science and Technology 10 (2), 2004, 137-14 5.

[25] Grima JN, Gatt R, Alderson A, Evans KE, An alternative explanation for the negative Poisson's ratios in α-cristobalite, Materials

Science and Engineering A 423, 2006, 219–224.

[26] Verma P, Shofner ML, Griffin AC, Deconstructing the auxetic behavior of paper, Physica Status Solidi B 251 (2), 2014, 289–296.

[27] Ma P, Chang Y, Boakye A, Jiang G, Review on the knitted structures with auxetic effect,

Journal of the Textile Institute 2016, http://dx.doi.org/10.1080/00405000.2016.1204901.

[28] Gibson LJ, Ashby MF, Harley BA, Cellular materials in nature and medicine, 2010, Cambridge University Press.

[29] Mandelbrot B, The fractal geometry of nature, Freeman, San Francisco, CA, 1982.

[30] Gaspar N, Smith CW, Miller EA, Seidler GT, Evans KE, Quantitative analysis of the microscale of auxetic foams, Physica Status Solidi 242 (2), 2005, 550-560.

[31] Alderson A, Rasburn J, Evans KE, Grima JN, Auxetic polymeric filters display enhanced de-fouling and pressure compensation properties, Membrane Technology 137, 2001, 6-8.

[32] Mir M, Najabat Ali M, Sami J, Ansari U, Review of mechanics and applications of auxetic structures, Advances in Materials Science and Engineering, 2014, Article ID 753496.

[33] Bohlman HH, Ducker TB, Levine AM, McAfee PC: Spine trauma in adults. In: Rothman RH, Simeone FA (eds.): The Spine, 3rd ed, vol. 2. Philadelphia: WB Saunders, 1992, 973–1166.

[34] Anghel M, Argeanu V, Talpo-Niculescu C, Lungeanu D, Musculoskeletal disorders (MSDS)-consequences of prolonged static postures, Journal of Experimental Medical & Surgical Research 14 (4), 2007, 167-172.