Study and development of concepts of auxetic structures in bio-inspired design

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Abstract: This work discusses the experience of using auxetic (negative Poisson's ratio) materials in different design objects, including chairs, bags, seat belts, etc., developed by the authors with their students. Auxetics have become of interest in engineering, whenever a support instead of a pronounced flexure, of a cellular, therefore lightweight material, is desirable. Structures have been calculated and modelled as chiral with defined geometrical parameters and then applied to concepts with the fabrication of real models using neoprene or generally rubbery material. Indications on the possible sensations of the user are suggested, which provided rationale for likely improved comfort and/or desirability of contact. Limitations of this study in terms of material experience appear the use of a single material as for auxetic properties and the focusing on one single possible auxetic structure, the chiral one. Despite this, this could be considered as a starting point for a possible database of material experience on the use of auxetics. From these considerations, it appears as the use of auxetic structures would lead to a more sustainable scenario for these objects, especially because improved user's experience would extend their duration of life and lead to a lower rate of discarded pieces.

Keywords: auxetic; chiral structures; Poisson's ratio; seat comfort; materials experience; bio-inspiration.

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1 Introduction

Inspiration from nature has been most recently widely linked to reference to design, due to enhanced knowledge of biological artefacts allowed by development of microscopy technologies enabling their exploration till the most concealed nanometric details. These possibilities are able to better disclose logic and principles that the intelligence of nature takes in specific domains (Santulli and Langella, 2010). In particular, use of materials performed in nature is generally speaking different from that of typical engineering applications. Rigidity tends to be coupled with flexibility and the conscientious use of voids results in weight reduction and possibility of producing various geometries (Vincent, 2009). A consequence of the above considerations is that nature makes wide use of cellular materials, such as honeycombs, although with a perspective very different from the one that is normally applied in engineering. Structural applications involve mainly materials arranged by series of aligned hexagonal cells with flat walls, therefore, forming convex polygons that can be treated normally as by Euclidean geometry considerations and therefore presenting a Newtonian mechanical behaviour. This is not the case of natural structures, which, as will be in more detail described here below, have different geometries for cellular bodies, involving concave polygons and the use of complex shapes with variable numbers of sides for each cell (Gibson, 2012). This led to the observation of a particular behaviour, which has no reference into Newtonian mechanics, in that the stretching of such a material would result in complex flexure behaviour of the bulk of it. This has been defined as 'auxetic behaviour' and in nature has found countless applications in many species (Liu and Hu, 2010). In contrast, in engineering, most applications do involve small structures subjected to quite significant tensile compressive action (e.g., braids or springs) (Subramani et al., 2014; Smardzewski et al., 2013).

It is rather obvious at this point that the design and production of engineered auxetic structures (it is important to note that auxetic behaviour is not linked to any particular material, but only to geometrical considerations) would change the experience of use of the artefacts that will be produced. At the moment, as for wearable items, therefore involving some contact with the user, slight auxetic properties are only shown by some microporous polytetrafluorethylene (PTFE) foams, mainly used to ease transpiration (Alderson and Evans, 1992). However, there is no evidence on how an auxetic structure could shape the experience of the user, for the novelty of this possibility and also for the difficulty of finding prevalent scenarios for the most suitable use of auxetic properties.

In this work, after a presentation of the possible auxetic structures, a number of case studies of concepts developed for their application in design are presented and the likely experience of their use is discussed, in continuous reference to what is in contrast perceived as the 'normal' or rather 'Newtonian' behaviour of these design objects. The idea in presenting these concepts is that human interaction with objects is linked to the fact that whenever cellular structures, therefore light and porous, are used, our experience with them is always linked to the fact that cells are usually described as convex polygons, normally hexagons. In contrast, the nature produces cellular structures with concave polygons with a variable number of sides, normally describable with the use of fractal geometry and which show auxetic properties. Since these are still design concepts, it is not possible at this stage to obtain objective data about factual experience: however, hypotheses are presented, which would ideally orient the discussion. This presentation would also enable offering a global idea of what could be the fields of application of these innovative materials, which would result in enhanced sustainability, as far as the experience of using these materials is satisfying, hence leading to a longer life of the artefacts.

2 Auxetic structures

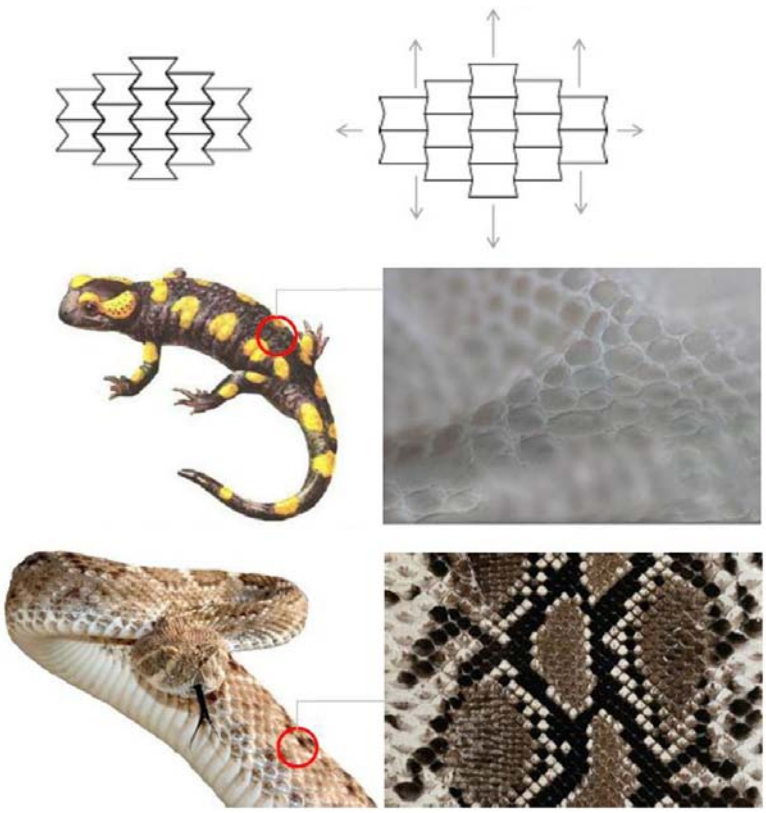
The word 'auxetic' derives from the Greek word 'auxetikòs', whose meaning is 'tending to increase'. Generally, materials are contracted in the direction orthogonal to load by reducing their section, showing 'necking'. Materials characterised from auxetic structures show an opposite behaviour by revealing a complex flexure, which results as a whole in an increased section in the direction orthogonal to load (Evans and Alderson, 2000). Auxetic behaviour is not related or specific to any particular material, being purely a consequence of how the material itself is structured microscopically. In engineering terms, Poisson's ratio is the ratio between the transverse and the longitudinal strain (ε_y / ε_x) produced by the application of a load F orthogonal to its section. Auxetic materials show a negative Poisson's ratio (NPR), ranging from 0 to –1, while common materials, also defined as 'Newtonian', have a positive Poisson's ratio.

Auxetic behaviour has been known in nature for more than a century now: a number of biological structures that present an auxetic behaviour are reported in Table 1 (Frohlich et al., 1994; Lees et al., 1991; Veronda and Westmann, 1970; Shahinpoor, 2011). For example, when the salamander moves abruptly around, as it is often the case whenever it needs to escape a predator, it is capable of adequately swelling, avoiding on the other hand applying excessive tearing forces on its skin (Frohlich et al., 1994) (Figure 1). A similar phenomenon occurs also in snakes' skin, whose non-Newtonian swelling is responsible for the so called 'concertina locomotion' by progressive variations of cells turgor and hence body elongation (Marvi and Hu, 2012) and also of the phenomenon of macrophagy, since an auxetic behaviour translates also in a negative linear compressibility (NLC) (Grima et al., 2012).

Table 1 Some biological structures presenting an auxetic behaviour

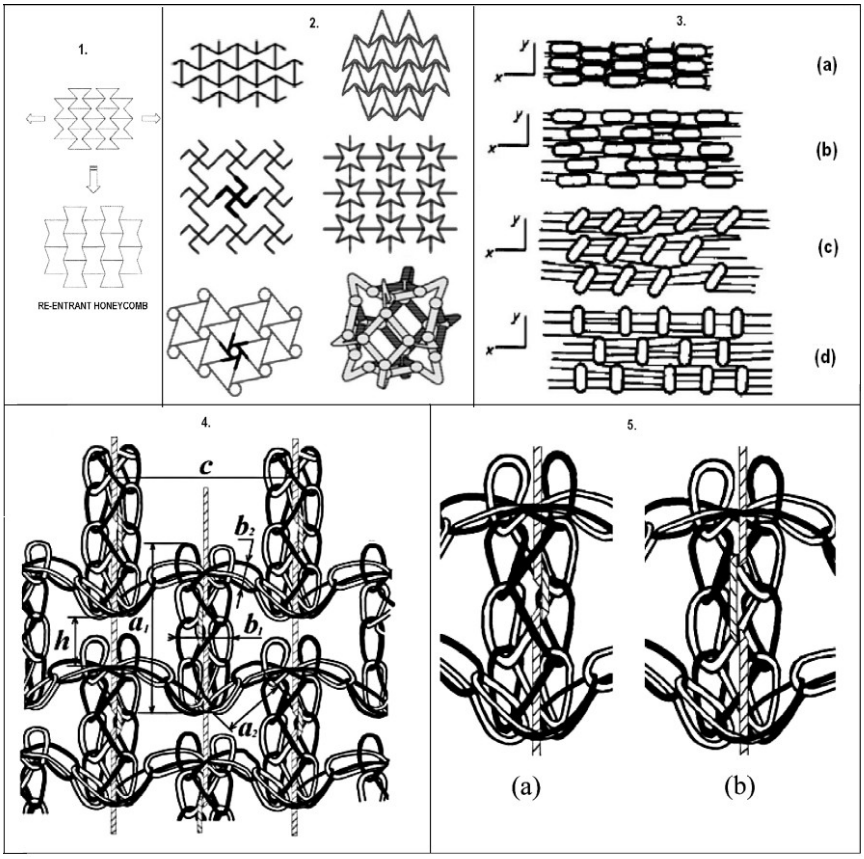
Biological structure	*Characteristics*	*Reference*
Skin of aquatic salamander	Composite made in sheaths with regularly organised collagen fibres in a crossed, fabric-like array	Evans and Alderson (2000)
Cow teat skin	Negative Poisson's ratio at low biaxial strains	Frolich et al. (1994)
Cat skin	J-shaped stress-deformation curve and out-of-plane auxetic behaviour	Lees et al. (1991)
Deployable structures (Dionaea, etc.)	Turgor pressure facilitated by the combined presence of cells with Newtonian and auxetic behaviour	Veronda and Westmann (1970)

Figure 1 Reference to the auxetic structure to the skins of salamanders and snakes (see online version for colours)



Note: Figure has been reconstructed from Frolich et al. (1994) and Lees et al. (1991), as regards the reptiles images.

Figure 2 Different types of auxetic structures



Notes: 1: Re-entrant honeycombs; 2: different forms of auxetic structures; 3: auxetic behaviour of laterally attached rods to polymers; 4 and 5: structure for auxetic textiles.

Source: Redrawn from Liu and Hu (2010).

Morphological studies on cellular structures have in particular been carried out, in particular to define by geometrical parameters some specific biological tissues, such as for example plant cells parenchyma. In the recognition that plant cells have curved edges and undulant faces, possibly with sigmoid curvatures, parenchyma was recognised as being a mixture of tetrakaidecahedral faces with other faces shaped as different polygons (Macior, 1960). However, it was only in 1987 that Rod Lake realised for the first time a sample of auxetic open cell polymeric foam using low density polyethylene by distorting under the action of heat the structure of inner cells, giving therefore to them some re-entrant vertices, so that the cell would form a concave polygon (Brandel and Lakes, 2001). This process was subsequently optimised and controlled by Chan and Evans with polyurethane foams, both with closed and with open cells (Chan and Evans, 1997). Caddock and Evans (1995) observed that PTFE (polytetrafluoroethylene) has an auxetic behaviour due to its microstructure of particles and fibrils, which can be assimilated on a smaller scale to the cells of re-entrant honeycomb, and had potential as for medical prostheses. Subsequently, Evans and Alderson (2000) disposed a process to produce by extrusion ultra-high density polyethylene fibres with a nodules and fibrils microstructure, hence, auxetic behaviour. More recently, researchers tried to evolve from honeycomb structures, for example, composite fibres have been realised, which are formed by a central elastomeric fibre, to which a thinner yet more rigid fibre is wrapped around: this structure revealed an auxetic behaviour (Yang et al., 2004).

In Figure 2, a number of different auxetic structures, potentially applicable to composite reinforcement and/or to its bulk structure, are presented. Starting from what could be called the pristine auxetic structure in that it is the one that most simply presents a form of repeated concavity, i.e., re-entrant (also referred to as 'bow-shaped' or 'accordion') honeycomb, in the other images different possible geometries are reported, which all have been calculated to have a NPR. In recent years, auxetic foams have been fabricated, which exhibit a shape memory effect, when subjected to load: they are able to recover their initial geometry, behaving as a consequence as Newtonian foams, hence with positive Poisson's ratios. The process can be repeated, reconverting the foam into a second auxetic state (Bianchi et al., 2010).

3 The 'auxetic design' project

As exposed above, envisaged contemporary applications for auxetic materials are mainly in engineering with limited, if any, interaction with the user. For this reason, this project concentrates in proposing new products able to exploit the characteristics of auxetic materials not only to solve mechanical and functional issues, but also to address particular needs that are more related to human factors, which do include comfort, transpirability, perceptive qualities.

The rapid diffusion of technologies for digital manufacturing associated to the evolution of parametric design software, offer new tools for the design and easier realisation of alveolar cellular structures with re-entrant vertices with auxetic behaviour to be evaluated and experimented as prototypes. This has brought a renewed interest and knowledge in respect of these structures and paves the way to new possibilities for interpretation on the design sector. This project takes its origin from the intuition of offering increased value to the properties of auxetic structures in applications that involve contact with the human body, as seat belts, bags, chair seats, benches, wearable fittings and even food. In all these cases, porosity becomes an opportunity to confer to the materials lightweight, filtering ability and transpirability, whereas the capacity of becoming thicker while withstanding a tensile load allows the user experiencing an increased 'softness' of the material.

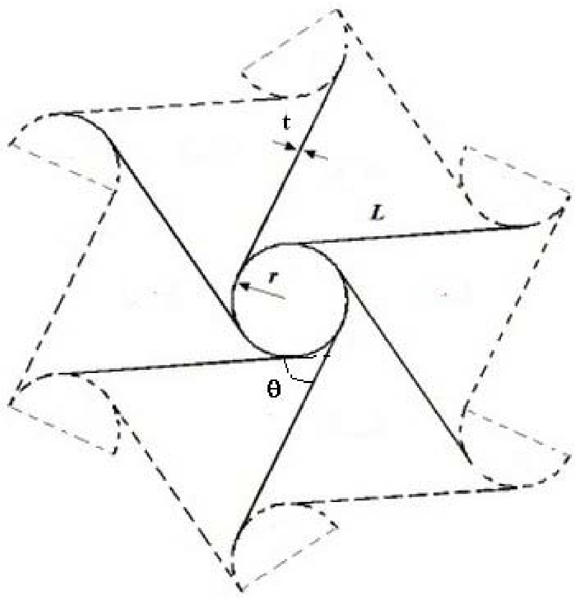
In the project, the base geometry used for the realisation of auxetic materials is the chiral structure, which was conceived, as mentioned above, first by Rod Lake. The term 'chiral', which comes from organic chemistry, here is intended to mean a physical property of spinning while deforming, due to the absence of a centre of symmetry. Chiral structures may have Poisson's ratios very close to the possible minimum, hence, –1 (Grima et al., 2008). The chiral cell has a fundamental unit formed by cylindrical elements, referred to as 'nodes', all with the same diameter, and rectilinear sections, called ligaments, which branch out tangentially to the nodes. The geometry of a chiral cell can be determined through a given number of parameters correlated by the algorithm that expresses relations to be respected for the behaviour of the structure to be auxetic. In particular, it is essential to calibrate the parameters L and R, indicating the length of the ligament and the radius of the cylindrical node, respectively; other parameters are the thickness of the ligaments and of the cylinders t and the angle formed between two consecutive tangent points, θ (Scarpa et al., 2007), as shown in Figure 3. In this way, a chiral structure was for example proposed as the internal layout of the wing box, allowing conforming deformations with the external flow, therefore acting as an aileron (Bornengo et al., 2005). A more extensive review of literature on auxetic structures is also available in Liu and Hu (2010).

The research group formed from Gianluca Cicala, Ludovica Oliveri and Giuseppe Recca had analysed different types of hexagonal chiral honeycomb structures (Newtonian, semi-re-entrant, auxetic) realised with a sample material with Young's modulus of 10 GPa and a Poisson's ratio value of 0.3. From their FEM analysis, the synclastic curvature of these structures emerged. In other words, the conventional alveolar materials tend after bending to assume a saddle shape, while the curve appears continuous for auxetic materials (Grima et al., 2010). Another characteristic that was deemed useful was the particular behaviour when undergoing indentation loading: the auxetic material behaves flowing towards the direction of the indentation point, therefore offering a larger resistance. As the Poisson's ratio approaches –1, the material becomes difficult to shear. Also, the hardness, H, is related to Poisson's ratio ν as:

$$H \sim (1-\nu^2)^{-x}$$

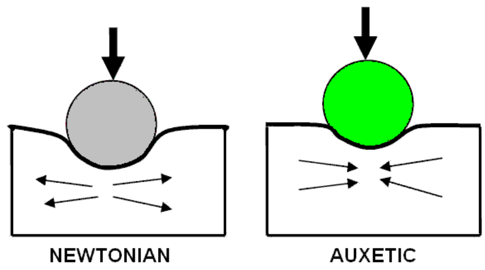
where x depends on the type of indentation. This effect is shown schematically in Figure 4 (Carneiro et al., 2013).

Figure 3 Parameters of the chiral honeycomb cell



Source: Redrawn from Bianchi et al. (2010)

Figure 4 Behaviour of a Newtonian and auxetic alveolar structures after indentation (see online version for colours)



4 Case studies

4.1 Chiral chair

Strictly speaking, nature designs no chair. However, a number of light yet resistant natural structures exist, which are able to shelter and sustain organisms. Typical examples are bird nests (Bailey et al., 2014), spider webs (Eberhard, 1990) and silkworm cocoons (Chen et al., 2012). Trying to elicit some of the characteristics common to these structures, which are geometrically very different from each other, a number of properties appear to be crucial for their success. These are: morphological flexibility, lightness, structural optimisation, transpirability, adaptability to variable loading conditions, and ultimately resilience, therefore the ability to withstand abrupt changes of environmental conditions. This last characteristic has a correlation with sustainability, in that it contributes to a longer and more successful life of the design object (Vezzoli and Manzini, 2008).

In our case, the main concept is that a seat, to be really comfortable, should be able to ‘change’ when varying the type of person who is sitting on it and on his/her body structure, so to be able to adapt also to their type of activity or rest needs. Auxetic structures could be applied to a chair seat for interior design to offer the opportunity to implement all the aforementioned qualities. In particular, the capability to swell the areas of the fabric structure that are in tension offers the opportunity to obtain a sort of ‘personalised’ cushion adaptable to the different anatomic configurations of the users e to their specific loading conditions. It has been recently clarified, though only numerically, that discomfort could be theoretically reduced by the application of an auxetic foam skeleton (in the relevant simulation the material selected is nylon): in particular, progressive load application would be advantageous, meaning that the seat is compliant for a smaller load, while becoming stiffer for increasing loads (Janus-Michalska et al., 2013). In other words, seat becomes therefore adaptable to the volume, weight and movement of the user, even if this is abrupt or repeated. The material porosity, associated to a non-allergenic and resistant material such as neoprene ensures comfort and wellbeing, but also structural optimisation, lightweight, reduction of the amount of raw material employed.

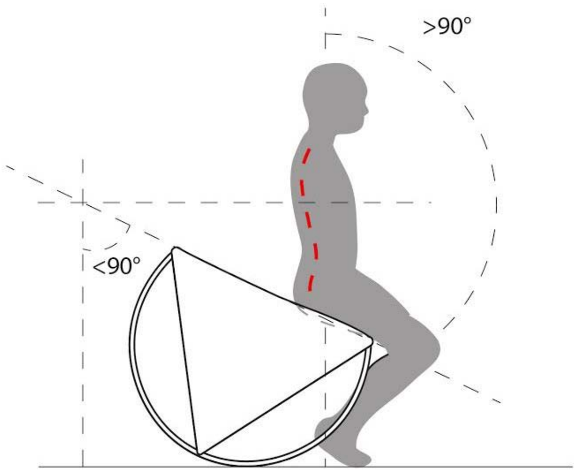
In the specific case, the auxetic structure is easily realised with water jet cutting using a chiral cell designed according to the parametric approach has a R/L ratio equal to 0.96, a value which gives an auxetic behaviour to the structure. The design of seat structure has therefore followed the principle of increasing as much as possible the mechanical strength of the fabric. The structure formed by cylinders and ligaments and tensioned tends to originate deformation mechanisms, in which some points of the structure modify their relative distance during movement, whereas others keep the same distance (Figure 5). Cell geometry determines a bending moment acting on ligaments that link the different nodes, which then determine a variation of cell surface, rather than a change of shape. This allows distributing stresses over a reasonably large portion of the structure, increasing in considerable way its resistance. At the very moment the user sits down, loading with his/her weight the structure allowing it to swell after an initial pressure and become more comfortable.

Figure 5 Chiral chair, horizontally pivoted fitness seat realised using fabric with chiral structure

Note: Two views and a detail of the auxetic structure contracted and extended.

Design innovation was not limited though to the project of material structure. For the chair design a hologrammatic principle was applied, which implies that the strategies leading the project in the detail of matter are proposed also at the macroscale and as regards the product functionality. Seat morphology and its macrostructure respond therefore to the exigencies of comfort and well-being that led to the choice to use the auxetic materials. To exploit as much as possible the possibilities offered by NPR, the structure underlying the auxetic material has been designed to be able to focus on the concept of well-being and on ergonomic concepts. In particular, a conventional chair, characterised by a reclined backseat creates some back bending, posing a considerable weight on the muscles of the lumbar region and on the spine. The theoretically corrected position is the vertical one, defined as orthostatic, which is kept while standing. In this way, the weight is loaded down the spine, thus avoiding any surcharge on the back. When sitting, however, the orthostatic position compresses abdominal muscles in a static way and becomes constrictive, especially if maintained for a long time. The human body, in fact, is not intended to be in a static position, likewise sitting, for a long time. Vertebral pains and pathologies are increasingly spreading and are due in considerable part to the fact that because of work commitments or lifestyle a sitting position is maintained for an exceedingly long time. Chiral chair is slightly higher than conventional chairs and presents a seat back forming an obtuse angle, of around 115°, so that the body weight can be unloaded along the legs and down to the feet. Also, this solution is not totally satisfying, according to ergonomic indications as regards the problem of prolonged constriction (Helander, 2003). For this reason, the concept involved a chair characterised by a 'virtual dynamism', therefore a pivoting movement in the longitudinal and transverse direction, inspired to fitball, a fitness tool based on an inflatable rubber sphere that is shaped when in contact with body anatomy and pivots as the result of body weight pressure, stimulating continuously neuro-muscular receptors in search of body balance determining a continuous contraction of the whole musculature. In other words, this creates a continuous muscular contraction and produces a kind of 'light fitness', which produces significant benefits, among which the improvement of the balance and the strengthening of the spine. As a matter of fact, sphere-sitting position has been used over the last decades for rehabilitation of slipped disc pathologies, to recover vertebral mobility (Kingma and van Dieën, 2009; McGill et al., 2006). A spherical support restores dynamically the body weight push produced by every movement (Figure 6). Beyond the condition of wellbeing, this type of chair facilitates also the standing and sitting acts, because when sitting the user is in a position closer to the standing one, therefore necessitates a lower mechanical stress to reach it. This satisfies the principle of lowest energy investment for best comfort that is characteristically present in many 'design tradeoffs' in nature.

Figure 6 Seating position on the chiral chair (see online version for colours)



The material selected to realise the Chiral chair is water-jet cut neoprene to form the seat with auxetic texture and steel tube frames to realise the load-bearing structure. The main characteristics for which this material has been selected are elasticity, shear and crushing resistance, capability to withstand heat, ageing, pollution, and the possibility of being inert towards a number of chemical agents, oils and solvents, therefore, it is easily cleanable therefore hygienic (Johnson, 1976). Finally, the adoption of the specific chiral structure can be translated in a texture useful for brand communication, which confers to it the characteristic of an unusual and unconventional object.

Along with the chiral chair also Cohy (Figure 7) has been designed: this is a self-cleaning bench for use in exteriors, which uses the material porosity not only for an improved comfort, but also to allow rainwater to flow down. Self-cleaning capacity is obtained through a neoprene seat with sliding auxetic texture, manoeuvred by the user by means a crank handle, which enables a part of the surface to come to contact with a brush and be therefore cleaned. Also, in this case, the seat is adapted to the conditions of use, thanks to the material and to the structure used, adaptable as a function of the service conditions, such as number of persons sitting, weight, and anatomical configuration.

Other concepts have been subsequently developed, which again apply the auxetic concept to other scenarios. These are briefly described as follows.

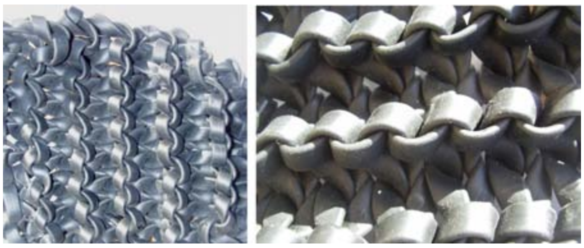
Figure 7 Cohy, self-cleaning bench for outside use with auxetic structured neoprene seat (see online version for colours)

Note: A general view and two detailed views.

4.2 Confort belt

The Confort belt (Figure 8) project of safety belt is based on the idea to pose alveolar auxetic tissue at the interface between the belt and the user's body so that when the belt undergoes tension, also in the case of slight braking, the material swells offering a 'cushion effect' which reduces the sensation of 'shearing' on the skin. The material porosity also increases the transpirability and therefore reduced discomfort especially when the belt is worn in direct contact with the skin. In the use of transportation vehicles that have to abide to safety normative of highway code, which do not agree to alternatives to the use of standard materials for belts (typically nylon) a cover is suggested to be superposed to the existing belts. In different fields such as those of high chairs or pushchairs for children, the material of the belt itself can be replaced by an auxetic fabric with high shear and tensile resistance.

Figure 8 Structures of the auxetic seat belt (real model in Neoprene) at two different magnifications (see online version for colours)



4.3 Auxbag

The same approach followed in the safety belt concept has been applied to shoulder straps for bags (Figure 9). The weight of the bag and the need to carry it for the whole day determine the need for the shoulder strap to be comfortable, soft, transpiring and dampening. From this need originates the choice to apply auxetic structures as shoulder straps, which tend to increasingly swell with load, thus creating a comfortable interface with the user's body.

Figure 9 Shoulder strap for auxbag, (a) simulation of the contracted position and (b) in the extended position (see online version for colours)

(a)

(b)

To shoulder strap, to obtain the auxetic bag, a hemp fabric was associated, tying it around the ends of the auxetic structure (Figure 10). Hemp had a long history in Italian material culture: nowadays it can be interpreted as a material for a future, where energies and materials are going to be renewable, highly effective and sustainable, both environmentally and socially. Hemp cultivation has a long tradition in Italy and Europe and has a limited environmental impact: it requires scarce amounts of water, has no need for pesticides and contributes to the correct exploitation of natural resources. In recent years, starting from 1998, the reintroduction of hemp in Italy has been promoted, which involves finding (or reviving) applications in different sectors (Ranalli and Venturi, 2004). In particular, in the textile industry, high added-value applications would contribute to increasing the success of hemp revival, through a design-centred production system. This would allow reinterpreting the hemp material, rebuilding as well its relation with the territory, which is crucial in some Italian regions, such as in Campania. On the other hand, it is very important for Italian design to invest on natural fibres as resources with high renewability and which present still a large number of possibilities for interpretation and transformation in a contemporary and sustainable key.

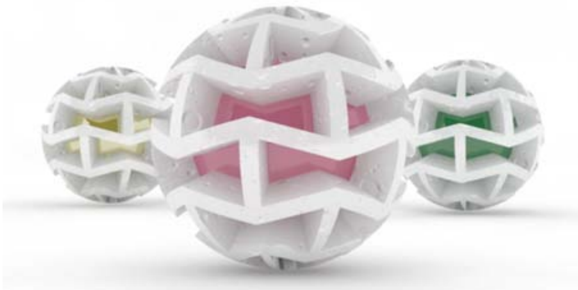
Figure 10 Connection between the auxetic shoulder strap and the auxbag (see online version for colours)

4.4 Auxetic candy

The auxetic structure has been proposed also in the food design field to a new concept of a line of candies based on principles of nutraceutics, hence, investigating the relation between food habits and health, analysing all the components or active principles of food with positive effects on health and on the prevention of some pathologies. The total diameter of the candy is 15 mm, where the auxetic skin is 5 mm thick, while the internal sphere has a diameter of 10 mm (Figure 11). The idea is that a very dense gel core, able to mediate the release of active principles is injected in the guar gum-based auxetic skin, which has been separately 3D printed (Santulli and Langella, 2013). The core is realised using a ‘composite’ material formed by a rubbery matrix made of malt, guar gum and carob syrup containing a heart of ingredients with particular antioxidants, immuno-stimulants, anti-inflammatory and depurative properties. The candy line is founded on the variation of the recipe of internal ingredients, such as petals, pollens, natural roots, cocoa, coffee, spirulina (blue-green alga) and curcumin.

The chiral porous microstructure with auxetic behaviour tends to swell when undergoing chewing action as the result of the NPR, limiting the release of principles placed internally, which becomes gradual. The slow release and the persistence of candy that tends to maintain the original dimension for a longer time both ensure a slow assimilation and a longer duration of taste and effect.

Figure 11 Auxetic candy (see online version for colours)



5 Discussion

The main objective that led the conception and development of auxetic materials had originally been the concept that a NPR would result in swelling of the material in response to loading and therefore the likeliness of early failure would decrease. A good example of this property are blood vessels made from an auxetic material, which will tend to increase their wall thickness in response to systolic pulses, thus preventing rupture of the vessel (Evans and Alderson, 2000). The main point of this discussion is trying to clarify whether and in what sense this effect may modify the experience of using materials: with this aim, a number of different objects have been developed in this design project to offer a wider perspective in several application fields and then lead to a more defined image of the 'auxetic experience'. Any improvement of the experience, as proved for example for waste-derived materials integration into design objects, results in improved sustainability for both more intense use and longer life duration (Eisenberg, 2013).

An initial consideration, though in the first instance qualitative, is that in general the use of auxetic materials may lead to an improved comfort: this might apply to all the objects developed in the project, even to the auxetic candy, which can be suggested to be more durable and therefore satisfying to taste. However, it is also obvious that the expressive-sensorial dimension of the use of auxetic material is not yet known, as there is no factual experience of using them yet. From a general point of view, it can be suggested that a starting point for envisaging the experience of using auxetic materials would be comparing them to cellular materials, of which they constitute a sub-system, though with opposite properties as regards tensile and compressive behaviour. In terms of the four theoretical charts (texture, touch, brilliancy and transparency) developed by Rognoli for educational purposes on materials experience, the most relevant in this case appear to be in this case the first two (Rognoli, 2010). In particular, the texture in auxetic materials is interestingly connected not only with the sensation of 'roughness' of the material, but is central to the capacity of the material to show its properties, related to NPR. As a consequence, the auxetic needs to be perceived as 'rough' in that the auxetic behaviour is obtained in practice by microstructuring the material, so that it cannot be homogeneous, although the sensation of roughness may be reduced when using a rubber material, such as neoprene (Stupkiewicz et al., 2014). In more general terms, as regards neoprene, it can be suggested that the expressive and sensory indications relative to the material, which in itself do not involve the auxetic properties, superpose with those relative to the texture, which in contrast yield the possibilities offered by NPR and NLC.

A further aspect that needs to be clarified is the interaction of the auxetic structure is the connection with other materials and/or structure: this is obvious in a number of aspects in our project, in particular, e.g., the connection with steel tubular in Chiral chair, with hemp fabric in the Auxbag and with the central core in the Auxetic candy. It is clear that the experience of using the auxetic structure is affected by the contact, hence, the comparison with the other material. It might be suggested for example that the Chiral chair may perceived as 'cold' in consideration of the presence of the steel support structure, whilst a natural material, such as hemp fabric, would rather contribute to its perception as 'warm'. It is interesting to note that a kind of sensation transfer of passing from a different material (non-auxetic) to an auxetic would in itself 'shape' the experience of using auxetic structures. From this comes the need to think of the interaction between auxetic structures and the materials surrounding them, especially critical in that auxetics have always been designed as self-standing structures, although this is unlikely to be the case for the best exploitation of their specific properties linked to the NPR and NLC.

6 Conclusions

This investigation tried to give a sense to the use of auxetic structures in different fields of design, trying to clarify what can be the users' sensations in the contact with them, with the idea of contributing to their wider acceptance. This would ideally go beyond the physical and engineering rationale to employ a NPR material, in particular whenever it is desirable to limit the flexure of a cellular structure. It is suggested that auxetics would in some cases improve the comfort of the user and in the main project that has been exposed, that of the Chiral chair, it would possibly guarantee an improved support to sitting with a less difficult and more natural standing up process. Also, the other projects would suggest that auxetics would improve contact with the user when desirable (e.g., giving a better sensation of control over a heavy bag), while reducing it in other cases (e.g., limiting the sense of 'shearing' when a seat belt is worn over light dresses or in contact with the skin). It is suggested that the realisation of these structures would improve the user's experience, thus leading to higher levels of comfort in the widest meaning of successful interaction with the five senses. This would result in a smaller amount of discarded pieces, such as in the Auxetic Candy, or in a longer life, for structures like Auxbag, etc., therefore, inherently making them more sustainable.

Two main difficulties need nonetheless to be pointed out, which could be the objective of further work. The first issue is the superposition of sensation from the ‘auxetic’ properties of the structure with the material specifically used to obtain the above (in the specific case of this study, neoprene or else other ‘rubbery’ material). The second one is accounting for the joining between auxetic and non-auxetic behaviour in a single design object, for example, a conventional bag with auxetic handle or strap: this could result in a mixed feeling, still to be investigated in more depth.

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