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APPLICATION OF DOMAIN INTEGRATED DESIGN METHODOLOGY FOR BIO-INSPIRED DESIGN- A CASE STUDY OF SUTURE PIN DESIGN

Velivela, Pavan Tejaswi;
Letov, Nikita;
Liu, Yuan;
Zhao, Yaoyao Fiona

McGill University

ABSTRACT

This paper investigates the design and development of bio-inspired suture pins that would reduce the insertion force and thereby reducing the pain in the patients. Inspired by kingfisher's beak and porcupine quills, the conceptual design of the suture pin is developed by using a unique ideation methodology that is proposed in this research. The methodology is named as Domain Integrated Design, which involves in classifying bio-inspired structures into various domains. There is little work done on such bio-inspired multifunctional aspect. In this research we have categorized the vast biological functionalities into domains namely, cellular structures, shapes, cross-sections, and surfaces. Multi-functional bio-inspired structures are designed by combining different domains. In this research, the hypothesis is verified by simulating the total deformation of tissue and the needle at the moment of puncture. The results show that the bio-inspired suture pin has a low deformation on the tissue at higher velocities at the puncture point and low deformation in its own structure when an axial force (reaction force) is applied to its tip. This makes the design stiff and thus require less force of insertion.

Keywords: Bio-inspired design / biomimetics, Design methods, Multi- / Cross- / Trans-disciplinary processes

Contact:
Zhao, Yaoyao Fiona
McGill University
mechanical engineering
Canada
yaoyao.zhao@mcgill.ca

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1 INTRODUCTION

Nature has supplied the inexhaustible resources for mankind, and at the same time, it has also progressively developed into a school for scientists and engineers (Luo et al., 2015). There are a lot of examples in the literature that shows the impact of bio-inspired design in terms of functionality and aesthetics. Bio-inspiration has been a source of ideas for many architects, designers, and material scientists to explore a variety of structures, surfaces, and material properties. Examples of bio-inspired design includes swimsuits inspired by sharkskin (Luo et al., 2015), super-hydrophobic surfaces inspired by lotus leaf (Zhang et al., 2016), and effective energy absorption structure inspired by bamboo trees (San Ha and Lu, 2020). However, integrating the bio-inspiration with the traditional problem-solving approach starts from the identification of the human needs and challenges and then defining and translating it into a biological challenge, followed by identifying the biological analogies that solves the need, translating that analogy into a technical solution. (Fayemi et al., 2015) listed the design methodologies related to bio-inspired design such as Design Spiral, BioTRIZ, Natural Language, and Functional Modelling such as IDEA-INSPIRE & DANE. (Nagel et al., 2018) categorised the bio inspired analogies into form, surface, architecture, material, function, process, and system. These approaches apply the existing biological functionality into a technical solution by a direct transfer, but do not address the multi-functionality aspect of design, that is combining different biological functionalities to get a design that solves more than one design problem. Figure 1 summarizes the application of bio-inspired design so far with the integration of traditional problem-solving approach. (Lenau et al., 2018) discussed about bio-inspired methods such as ISO Design methodology, ParisTech design method, DTU biocards, and Biomimicry institute's Design Spiral methodology. All the methods discussed are aimed at solving a problem by applying a direct emulation of a biological source of inspiration. A study by (Svendsen and Lenau, 2019) suggest that supporting designers in converting a problem driven bio-inspired design to a solution driven bio-inspired design during the early stages of bio-inspired design process aids in multifunctional solutions.

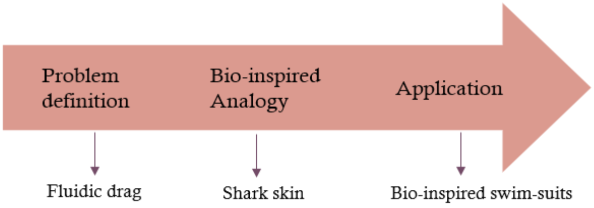
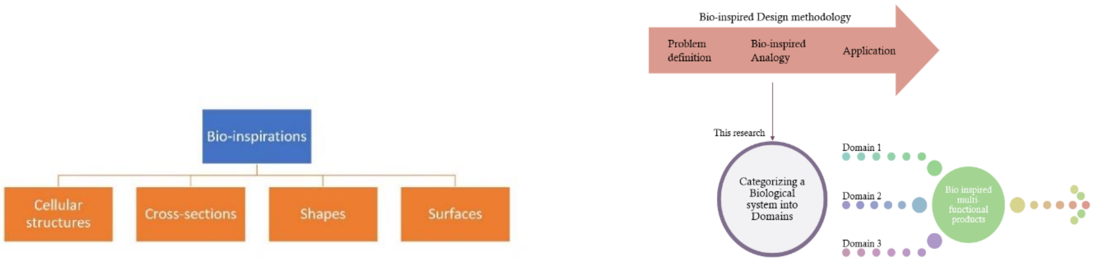


Figure 1. Representation of the application of bio-inspired design so far with the traditional problem- solving approach.

In this research a new design methodology, called as Domain Integrated Design is proposed. This method explores the integration of domains to achieve multi-functional structures. A case study was carried out following this method to design a bio-inspired suture pin. In this case study, combination of the functionalities of two different organisms were used to obtain a multifunctional bio-inspired suture pin design. A conceptual design of the bio-inspired suture pin inspired from a kingfisher's beak and a porcupine quill was created. The unique rotational parabolic cross-section design of a Kingfisher's beak which makes it easy for it to catch its prey moving from low dense material air to a high dense material water, without a splash is the basic structure of the pin (McKeag, 2012);(Haubursin, 2017). Adding on to its structure, integrating it with porcupine quills as the micro barbs present on the quill enables the structure to insert quickly into the skin and tough to take out. Thus, integrating both features, a new bio-inspired suture pin design is developed that will have a low puncture force and stays in the skin until the wound heals and being resistant from external disturbances. The next sections will define the proposed Domain Integrated Design, and a case study which involves in design, development, and analysis to support the proposed methodology.

2 THE PROPOSED DOMAIN INTEGRATED DESIGN APPROACH

From the literature, there are two different approaches that support the bio-inspired design or biomimicry namely, Top-Down and Bottom-Up. According to (Moheb Sabry and Amr, 2016), the Top-Down approach defines the human needs or defining problem and looking to the ways and other organisms or ecosystems solve. The Bottom-Up approach involves in identifying a particular characteristic, behaviour, function in an organism or ecosystem and translating that into human designs. The proposed Domain Integrated Design method moves into the next phase of identifying the biological functionalities into basic domains. This helps designers in identifying the basic elements that are responsible for a particular function in a biological entity. The biological functionality is categorized into four major domains in this research namely Surfaces, Shapes, Cross-sections and Cellular Structures as shown in Figure 2 (a). For example, the box-fish shape that reduces the aerodynamic drag is categorised as a cross-section domain. Similarly, lotus leaf would exhibit super-hydrophobicity because of the nanostructures is categorised as surface domain. The multi-functionality is achieved by the combination of the identified domains.



(a) *(b)*

Figure 2. a) The proposed classification of the functionality of a biological entity into domains; b) Domain Integrated Design approach

Figure 2 (b), explains the transition between the so far bio-inspired design methodologies and the Domain Integrated Design approach. Instead of focusing on the direct transfer of application of identified biological functionality as a solution to an engineering problem, the proposed method takes a step further to solve more than one engineering problem form classifying the identified biological functionalities into various domains and by using different combinations of those domains. The primary focus of this research will stay at the conceptual design phase which involves in brainstorming, sketching and embodiment. The design phase also involves with the selection of materials for the design. The decisions like the design, material and costs are committed at an early stage thus profiting from less manufacturing costs and enhancing innovation (edx, 2020). The following sections will detail the case study to validate the proposed design methodology.

3 NEEDLE-TISSUE INTERACTION - (PUNCTURE FORCE AND TISSUE DEFORMATION)

To understand the design requirements of suture needle, it is imperative to understand needle tissue interaction especially the puncture force and tissue deformation during operation. This section provides an overview on various experiments conducted on needle-tissue interactions, with varied needle shapes, insertion velocities and insertion angles. (Bao et al., 2016), (Chebolu and Mallimoggala, 2014); (Li et al., 2017) identified the following factors as they influence the puncture force and tissue deformation.

- Stiffness: The puncture force depends upon the stiffness of the needles.
- Influence of velocity: The first puncture force becomes significantly less due to increase in insertion velocity.
- Influence of angle: The puncture force is the lowest when the angle reaches 90 degrees that is, when the needle punctures vertically into the tissue surface

In an experimental study of calculating deformation of needle, a trocar needle was inserted into five phantom specimens at the same velocity of 2.5 mm/s. In the study they found that the reaction force (at the time of puncture) on the needle was about 0.90 N and the volume of tissue deformation gets to its maximum at the puncture point (Dedong et al., 2013). The above experiments from literature provide that the puncturing force depends upon the stiffness, insertion velocity, insertion angle and the shape of the needle tip. The simulation and validation for the bio-inspired suture pin are done based on the above-mentioned factors. In this research, a conceptual design of a new surgical staple leg is presented using the combinations of a kingfisher's beak and porcupine quills to achieve multifunctionality. The kingfisher's beak is used to reduce the pain in patients by reducing the force of insertion, the quills of a porcupine is used for preventing the suture pin form removal and from external disturbances. Throughout this paper, the newly designed surgical staple-leg is termed as bio-inspired suture pin-leg/needle. The following sections provide the design and simulations in detail. In this research, the validation of the bio-inspired suture pin-leg/needle design is done on two criteria namely, deformation of tissue at the puncturing moment and the deformation of the needle at the puncturing moment.

4 HYPOTHESIS AND DESIGN

From the existing literature as discussed in section 1, and the proposed Domain Integrated Design from section 2, a hypothesis can be derived that the rotational parabolic cross section of a kingfisher's beak that is typically used at high velocities to penetrate from low density region to high density region to catch its prey will be the most suitable for a suture's pin-leg structure. In addition to the rotational parabolic cross section, the triangular micro projections inspired by a porcupine quills i.e., the barbs were introduced to prevent the suture form removal. From the proposed methodology, the following domains are integrated for the design of a bio-inspired multifunctional suture pin legs/needle.

- **Cross-Section (Domain-1)**: The rotational parabolic cross-sections are typically used for high velocity penetration applications can be used as a suture pin equivalent. Using such bio-inspired cross sections will reduce the penetration forces. For example, in bio-medical applications and for drilling equipment
- **Surface (Domain-2)**: Addition of surface features such as *barbs* of porcupine quills will give us a new dimension of multifunctional structures (Karp, 2014).

To validate the hypothesis derived from the proposed methodology, the case study of the design of bio-inspired suture pin-leg/needle is discussed in this paper. In this paper, the design is approached by integrating the domains of cross-sections and surfaces. Figure 3 shows the difference between conventional surgical staple pin and bio-inspired suture pin-legs/needle.

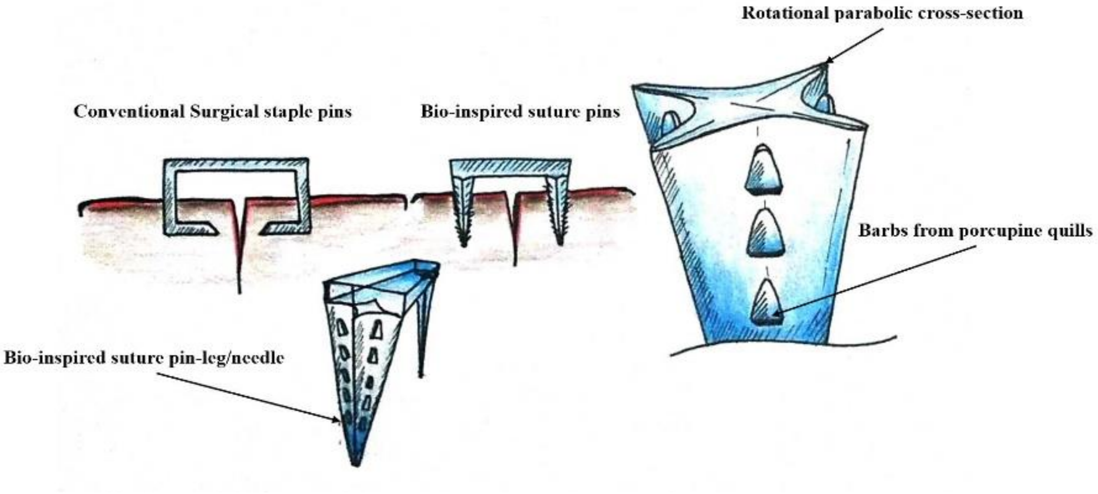
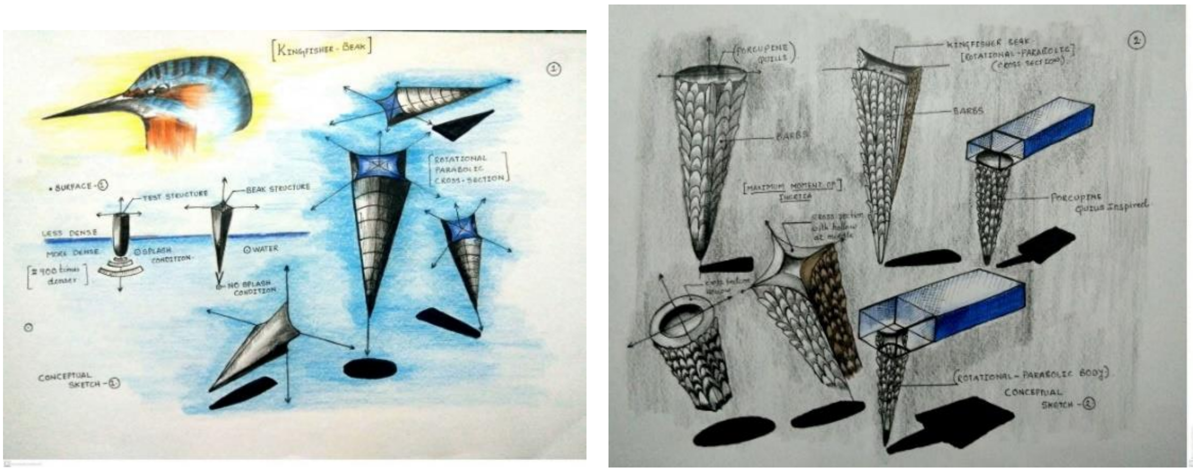


Figure 3. The sketch of conventional surgical staple pins and the bio-inspired suture pin-leg/needle.

For the design, the dimensions of the Johnson & Johnson's staple leg are taken as a reference from the wound closure catalogue of the Ethicon surgical tools. PXW35 is used for head skin closure, and its leg length is chosen for the design (Ethicon).

4.1 Product Sketching

The crucial stage of any product development process starts with the visual representation of the product. Figure 4 (a), depicts the rotational parabolic cross-section inspired by the kingfisher's beak and its ability to cruse from a low-density region to a high-density region. Figure 4 (b), depicts the ideation of porcupine quills with microstructural barbs and transforming it into a rotational parabolic cross-section and integrating it with the microstructural barbs. For the design and analysis of the bio-inspired suture pin-leg/needle, a solid rotational parabolic cross-section is chosen for the simplicity of the design process.



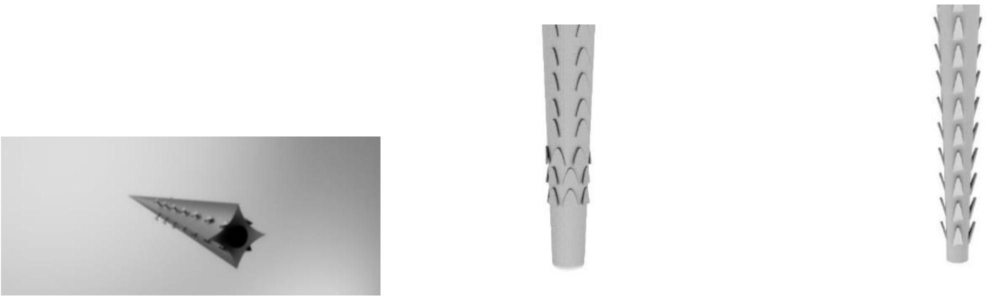
(a)

(b)

Figure 4. a) The conceptual sketch of kingfisher's beak with its rotational parabolic cross-section; b) The conceptual sketch of bio-inspired suture pin-leg/needle

4.2 Detailed Design

This section defines the embodiment phase of the design process, where the bio-inspired suture pin-leg/needle is modelled using available 3D modelling packages. In this research, Rhinov6, and Autodesk Fusion-360 were used for modelling the bio-inspired suture pin-leg/needle. Figure 5 (a) depicts the initial stage of the design, where the barbs from porcupine were attached to the cross-section by the small overhanging attachment. Figure 5 (b) depicts the improved design of the barbs and their attachment with the surface of the legs cross-section. Figure 5 (c) shows the improved design with the barbs integrated with the surface.



(a)

(b)

(c)

Figure 5. a) Design 1 with the initial stage of development of legs; b) Design 2 with improved design of barbs c) Design 3 with improved design and placement of barbs

Table 1 shows the dimensions of each micro barb integrated with the rotational parabolic cross-sectional structure.

Table 1. Dimensions of the barbs used in the design.

S. No	Length	Breadth	Thickness
1	0.1 mm	0.05 mm	0.01 mm

Table 2 shows the dimensions of the rotational parabolic cross-sections with the bottom tip and the diameter of the circumcircle at the top.

Table 2. Dimensions of the leg used in the design.

S. No	Bottom tip diameter	Circumcircle diameter at top	Length of leg
1	0.02 mm	0.58 mm	3.9 mm

For the simulation, the design shown in Figure 5 (c) is chosen. For the material selection criteria for the bio-inspired suture pin-leg/needle, we chose biodegradable metals that are designed to degrade in the body during or after their function is performed. Typically, this function would be as an implant to support tissue growth in particularly in orthopaedic, cardiovascular, and paediatric use. Current biodegradable metals are Magnesium (Mg) or Iron (Fe) based (Poologasundarampillai and Nommeots-Nomm, 2017); (Divya et al., 2019). These metals will perform the healing of the affected tissue followed by the generation of new tissue and start to degrade slowly (Sangeetha et al., 2018). Magnesium alloys have shown great potential for applications in bone tissue repair. They possess remarkable physical and mechanical properties such as an elastic modulus to that of a human bone (Griesser, 2016). For this research, the bio-degradable materials such as Iron and Magnesium alloy are used (Sangeetha et al., 2018); (Divya et al., 2019).

5 SIMULATION AND RESULTS

The simulation of the deformation of tissue at the puncturing moment was performed using ANSYS R2020 Student Version. The experimental step involved in modelling the leg and the tissue epidermis layer using RhinoV6 and Spaceclaim 2020, respectively. The material for epidermis/Human tissue is chosen to be Polyurethane (Dąbrowska et al., 2016) as it has the properties that mimic the human tissue. As discussed in the section 4.2, the material for the suture was chosen as Iron, because pure iron (Fe), Fe-35 Mn alloy, magnesium alloy are potentially candidates for cardiovascular stent applications. cardiovascular and orthopaedic applications (Sangeetha et al., 2018); (Divya et al., 2019). The simulation of the impact of the bio-inspired suture pin-leg/needle and the conventional suture at various velocities on the surface of the human epidermis was simulated by using the Explicit Dynamics solver of the ANSYS R2020 Student. For the simulation of the deformation of the bio-inspired suture pin-leg/needle at the puncturing moment, static-structural analysis solver of ANSYS R2020 Student was used. An auto-generated meshing strategy is used for both the simulations. The material for this simulation is chosen as Magnesium alloy. The reaction forces are applied on the tip surface and on the tip edge, respectively. The simulation results are compared with the previous experiments that were done on the needle interactions as discussed in section 3. The following sub-sections provides the tabular columns of the materials chosen as well as the results of the simulations.

5.1 Simulation (Explicit Dynamics)-Measuring the total deformation on the tissue.

The explicit dynamics was performed on the suture without the barbs on the surface. This is because, the first contact point will be the Kingfisher's rotational parabolic cross-sectional tip and the barbs are not placed at the tip of the needle. The assigned velocities for bio-inspired suture pin leg/needle and conventional needle are 1 mm/sec, 2.5 mm/sec and 5 mm/sec. The material assigned for the conventional suture pin was Iron, same as in the case of bio-inspired suture pin-leg/needle. This is chosen because to avoid the bias in results if the simulation is performed using two different materials. The thickness of the epidermis layer is chosen form article on topography thickness of skin on human face (Chopra et al., 2015), and the average value is taken as 0.08 mm.

Table 3 and Table 4 depicts the deformation of the tissue surface/epidermis at the velocities of 1 mm/sec, 2.5 mm/ sec and 5 mm/sec by bio-inspired suture pin-leg/needle and conventional needle respectively. The deformation of the epidermis layer is less in the case of bio-inspired suture pin-leg/needle tip as compared to that of a conventional needle tip.

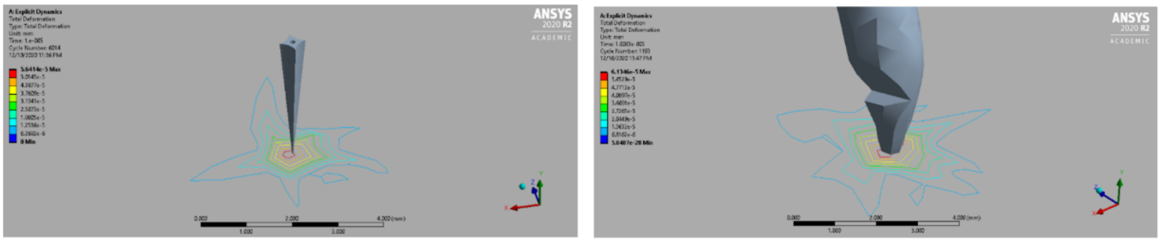
Table 3. Results of total deformation by the impact of bio-inspired suture pin leg/needle on to the human tissue/epidermis at various velocities

S. No	Insertion velocities	Total deformation in mm (Max)
1	1 mm/sec	1.13 e-5
2	2.5 mm/sec	2.8212 e-5
3	5 mm/sec	5.641 e-5

Table 4. Results of total deformation, by the conventional needle on the human tissue or epidermis at various velocities

S. No	Insertion velocities	Total deformation in mm (Max)
1	1 mm/sec	1.225 e-5
2	2.5 mm/sec	3.006 e-5
3	5 mm/sec	6.1346 e-5

Figure 6 (a) and (b) respectively show the impact simulation of the bio-inspired suture pin leg/needle and the conventional needle at the velocities at 5 mm/ sec. In all the three cases the deformation increased but at the higher velocities the deformation is larger in proportion in the case on conventional needle, when compared with the bio-inspired suture pin-leg/needle. This explains that at higher velocities the bio-inspired suture pin-leg/needle will have a less damage or deformation of the epidermis/human tissue. This clearly states that the rotational parabolic cross-section works well at the higher velocities of insertion.

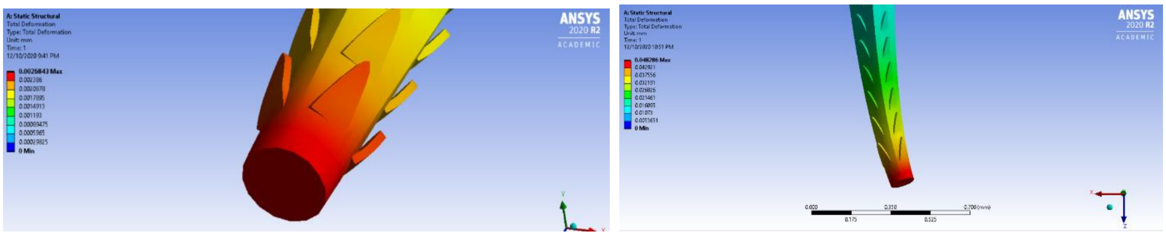


(a) (b)

Figure 6. a) Tissue deformation form a bio-inspired suture pin leg/needle; b) Tissue deformation from a conventional suture needle at 5 mm/sec.

5.2 Simulation (Static Analysis)-Measuring the total deformation of Needle.

Application of an axial force (reaction force at puncture point) of 0.90 N was chosen from the analysis of experiments done on needle tissue interactions as discussed in section 3, and the total deformation of the needle is simulated. The maximum deformation occurs at the needle tip that is at the point of application of the reaction force. Figure 7 (a) and (b) depicts the application of the reaction force acting on the needle in two different scenarios. The first being the force acting on the entire surface of the needle tip (case 1) and the second being the force acting on the edge of the needle tip (case 2).



(a) (b)

Figure 7. a) The deformation by application of axial (reaction due to puncture) load on the needle tip surface (case 1) b) The deformation by application of axial load (reaction force due to puncture) on the tip-edge (case 2)

In both the cases the deformation is minimum and this explains that the structure pin is stiff enough and requires less force of insertion.

- The deformation of tissue from conventional suture needle is high due to large surface interaction and in the case of bio-inspired suture pin leg/needle, a much reduction in deformation of the tissue is observed.
- The increase in the velocity improved the results in the case of bio-inspired suture pin-leg/needle. The inspiration from kingfisher's beak is verified as it is primarily used to travel from low density medium to high density medium at high velocities.
- In the case of application of axial force, and the total deformation on the bio-inspired suture pin leg/needle is small and thus the stiffness is quite high. This verifies that the puncture force for bio-inspired suture pin/leg is very less as compared to that of the conventional needle.

In criteria 1, as mentioned in section 5, the simulation was performed using Iron as the material assignment and in criteria 2, the simulation was performed using Magnesium alloy as the material assignment. Both Iron and Magnesium alloys are being bio-degradable materials as discussed in section 4. In both the simulations the bio-inspired suture pin-leg/needle showed better results as compared to that of a conventional needle.

6 CONCLUSIONS

This Domain Integrated Design methodology was presented in this paper which is a unique approach that classifies the identified biological functionalities observed in a biological entity into domains. These domains are classified as cross-sections, shapes, cellular structures, and surfaces. This methodology has the advantage of ideating and designing multi-functional structures, from different combinations of the classified domains. As a case study, a bio-inspired suture pin-leg/needle design was carried out following the proposed methodology. Simulation was conducted to examine the advantage of the bio-inspired suture pin-leg/needle design over the conventional sutures/needles. The simulation results show that the tissue deformation was low for bio inspired suture pin leg/needle at high insertion velocities as compared with the conventional suture needle. On the other hand, Bio-inspired suture pin-leg/needle has an extremely low deformation on its structure when the axial force that is, the reaction force at the puncture moment was applied. From the results, it shows that the Bio-inspired suture pin-leg/needle has high stiffness and hence it requires a low insertion force. This helps to reduce the pain in patients while suturing. Moreover, the barbs on the bio-inspired suture pin-leg/needle helps to stays in the skin until the wound heals and being resistant from external disturbances. The future work of this research includes sub classification of domains into sub domains comprising of structures at the nano and the micro scale. Further investigation will be done to see how sub-domain combinations will work to design multi-functional and multi-scale structures.

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