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Generative design of joint contact surfaces inspired by biological morphogenesis

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Abstract

Recent knowledge about biological joint morphogenesis opens new perspectives in mechanics to automate joint contact surface design. The present work evaluates the feasibility of a generative design method inspired by the joint morphogenesis process to develop contact surfaces. A finite element model of joint morphogenesis reported in literature was implemented. This morphogenesis process was adapted and implemented for mechanical applications. The results show that the bioinspired joint shaping process adds matter in the zones next to the contact zone decreasing the contact pressure (up to 57%). The results demonstrate the feasibility of implementing biological growing rules in generative design.

Biologically inspired design, Geometry, Stress

1. Introduction

Improving the engineering design process is a subject of interest for science and industry. Hence, several theories and methodologies have been developed [1], most of them as decision support tools. Computer-automated tools have been proposed to help engineers in the different phases of the design process. For the detailed design of mechanical parts, several automated approaches have been proposed; they can be classified into topology [2], shape [3] and size optimization [4]. These methodologies are specialized in structural design and are less applicable to mechanical joints. Currently in mechanical design, geometry of contact surfaces of a joint is imposed by the designer, usually resulting from technological background. The literature about mechanical joint design has been mainly focused on the optimisation of roller bearings contact profiles [5] and gears lead contact profiles [6] under normal loads. Although the proposed solutions have contributed to improving the load transmission performance of mechanical joints, they cannot be easily generalized to other loading conditions. Additionally, the manufacturing costs have limited the development of new mechanical joints made up of free-form contact surfaces, even if it allows to increase the durability of the systems [3]. However, current sustainability trends suggest reviewing our design practices [7].

For its part, vertebrates have already been confronted with the mechanical problems mentioned above: optimization of load transmission, durability, energy efficiency and frugality. With many biological solutions offered to us by nature, bioinspiration is an emerging field in engineering design [8]. Some structural design methodologies have been inspired by natural objects or processes. Recent knowledge developed by biologists on the natural process of joint shaping (joint morphogenesis) [9] opens new perspectives. The knowledge behind the process of joint morphogenesis could be used in mechanical design to automatically shape functional contact surfaces. However, the application of the joint morphogenesis rules cannot directly be used in a mechanical context because of the differences in the operating conditions (material properties, contact conditions, and self-repairing capacities). Based on this, the research question investigated in this work is: how to adapt the joint morphogenesis process to design of contact surfaces? In order to answer this question, the present work evaluates the feasibility of a generative design method inspired by the joint morphogenesis process to design functional contact surfaces.

2. Synovial joint morphogenesis

2.1. Joint morphogenesis theory

In synovial joint morphogenesis, the shaping of contact surfaces is due to a smart growth of the cartilage tissue. Studies have shown that cartilage growth might be regulated by mechanical stimuli. According to Carter's theory [9], the behaviour of the chondrocytes (cartilage tissue cells) is highly dependent on the shear octahedral stress (or von

Mises stress) (σ_{VM}) and the hydrostatic stress (σ_{hyd}). Von Mises stress promotes the ossification of the cartilage through the stimulation of the chondrocyte hypertrophy, whereas the compressive hydrostatic stress inhibits the ossification by keeping the cells in a proliferative state [9]. Experimental studies have shown that static compression stress inhibits cartilage growth, while dynamic compressive stress, conversely, promotes it [10]. In addition to mechanical stimuli, cartilage growth is also affected by some biochemical factors.

2.2. Morphogenesis theory for mechanical applications

Synovial joint morphogenesis is a frugal shaping process in which nature disposes of matter in a very selective way. In contrast, the design of mechanical joints is usually driven (or even constrained) by the manufacturing costs. Hence, for ages, mechanical parts have been made up of simple geometries (planes and cylinders). As described by [9], growth rules of the biological joint morphogenesis process are physically analogue with the multiaxial fatigue failure criteria; both are affected by cyclic von Mises and hydrostatic stresses. Hence, there exists some knowledge behind this biological process that has not been used yet in mechanical design to automatically shape functional contact surfaces.

2.3. Computational models of joint morphogenesis

During joint morphogenesis, local tissue growth, directly related to chondrocytes proliferation, is defined as locally isotropic. That means that the growth tensor \mathbf{G} can be assimilated to a scaled identity tensor \mathbf{I} , as $\mathbf{G} = \gamma \cdot \mathbf{I}$; where γ is the growth magnitude. This means that the shaping of biological joints is dependent on the magnitude of γ so that some areas grow faster than others, locally and iteratively adapting the geometry. Representing the mechanical and biological growth factors, the growth tensor \mathbf{G} can be divided into two parts:

$$\mathbf{G} = (a_1 \cdot C_b + a_2 \cdot C_m) \mathbf{I} \quad (1)$$

with C_b and C_m biological and mechanical contributions, respectively. The constants a_1 and a_2 correspond to the strength of the mechanical or biological stimuli regarding the overall growth. C_b is related to the chondrocytes' density [11]. C_m is defined by σ_{VM} and σ_{hyd} . From this base, several research works have proposed computational models about the joint morphogenesis process. The first one was developed by [11] who considered that only the positive σ_{hyd} promoted cartilage growth. Later, [12] proposes a model in which the cartilage growth was regulated by the negative σ_h , and they were the first to include the synovial capsule (as a spherical incompressible domain surrounding the cartilaginous bone rudiments). This model was enhanced by [13] including the effect of the von Mises stress (σ_{VM}) as a growth inhibitor in the regulation of the articular cartilage growth. All models found in the literature follow an iterative loop, in which the tissue grows on each step until a stop criterion is reached.

2.4. Implementation of a joint morphogenesis computational model

The starting point of this work was to replicate a computational model of a joint morphogenesis existing in the literature. The implemented model was the one presented in [13]. From that work, we simulated the case of the morphogenesis of an interphalangeal joint developing under palsy conditions. The initial geometry, material properties and boundary and loading conditions were reproduced as closely as possible. A mechanical simulation was performed to calculate the stress state of the bone rudiments. Then, σ_{VM} and σ_h stress fields resulting from this simulation were extracted. These values were used to calculate the field of C_m (see Eq. (1)). C_b was calculated following the same procedure of [11]. A ratio of $a_1/a_2 = 0.1$ was considered to weigh C_b and C_m . The growth magnitude γ was considered as a temperature in a thermal expansion simulation to imitate the tissue growth (as it has been done in [12]). Thermal and mechanical problems were solved with finite element methods and implemented in the open-source (finite element analyses) FEA software tools Salome-Meca and Code-Aster. At the end of each iteration, the computed deformed geometry was extracted in a stress-free condition so the loading conditions could be applied again for the next step of growth.

The results of the reference study and those of our simulation can be seen in Fig. 1(a) and (b), respectively. The simulation lasted 7 steps as in the reference study. Contact surfaces from both models converged to the same shape. In both simulations, the bottom surface of the distal phalanx evolved into a concave shape, whereas the upper surface of the proximal bone converged more to a convex one. Although the obtained geometry is like the biological reference, the load transmission performance was not evaluated. Then, this implementation of joint morphogenesis was adapted to a mechanical context to assess its applicability for the generative design of contact surfaces of mechanical parts.

3. Bioinspired design of contact surfaces of mechanical joints

In order to adapt the concepts of synovial joint morphogenesis to the design of contact surfaces of mechanical joints, two contexts were defined: one related to the application case and another related to the morphogenesis process (see Fig. 2). The application context (Fig. 2.a) is the one in which the materials (Young's modulus E and Poisson's ratio ν) and the load (\mathbf{F}) imposed by the design case are considered.

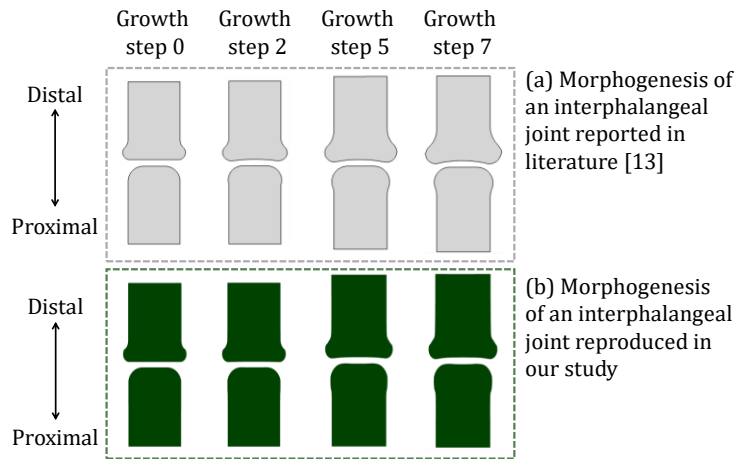


Figure 1. Results of morphogenesis of an interphalangeal joint developing under palsy conditions from (a) a biology study from literature [13] and (b) this study.

In the application context, the contact pressure and stress distributions are calculated to evaluate the load transmission performance during the simulation. Load transmission between parts is considered by means of direct dry contact. The morphogenesis context (Fig. 2.b) is an abstract context in which the shaping of the “morphogenesis pieces” takes place. This context simulates the cartilaginous state of the bones during the first stages of the morphogenesis, with a load \mathbf{F}_m . In the morphogenesis context, load transmission between parts is done through a capsule (equivalent to a synovial capsule) represented in light blue in Fig. 2b. The contact zone susceptible to growth is called hereafter malleable zone and represents the epiphysis in a biological context (region represented in yellow in Fig. 2b). The proposed bioinspired algorithm (presented in Fig. 3.) requires as inputs an initial geometry of the mechanical parts, the loading conditions and the material properties of the application case. The mechanical parts adapt their shape according to the mechanical stimuli following bioinspired growing rules. The obtained geometry is evaluated in the application context at each iteration by means of the peak contact pressure, hydrostatic stress and von Mises' stress. Hereafter, each step of the algorithm is explained.

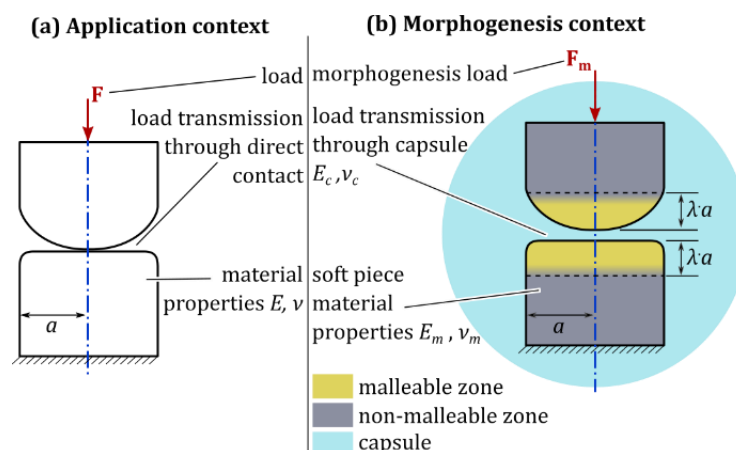


Figure 2. Equivalences between: (a) the application and (b) the morphogenesis contexts for the bioinspired design of contact surfaces.

Create initial mesh. The first stage of the biological joint morphogenesis process is the cavitation, where the bone rudiments and the synovial capsule develop. In the bioinspired design algorithm, this stage corresponds to the creation of the initial geometry of the parts in contact. Using this geometry, the capsule is then created with Boolean

operations. The capsule is considered as an incompressible domain surrounding the joint [12,13]. Afterwards, the contact parts and the capsule are meshed. The Young's modulus of the capsule was defined in function on that of the mechanical parts: $E_c = E/1000$, as in other studies [13].

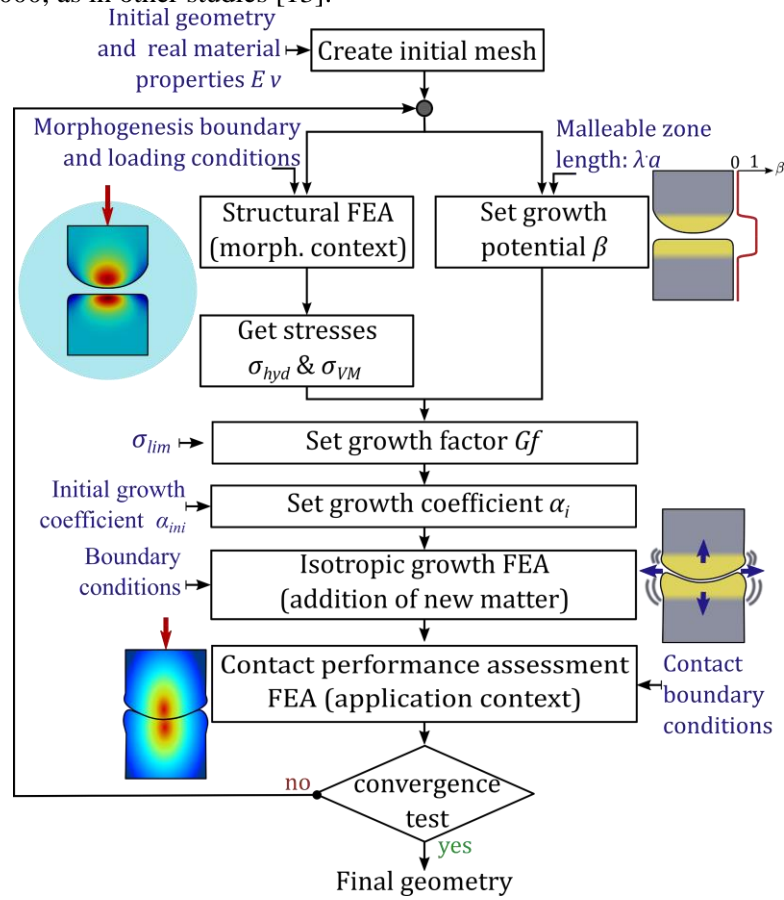


Figure 3. Flowchart of the proposed methodology for the generative design of contact surfaces inspired by biological joint morphogenesis.

Structural FEA (morphogenesis context). Cartilage growth is mainly regulated by the mechanical stimuli generated by the interaction of the bone rudiments. In the bioinspired design algorithm, this mechanical interaction is simulated by means of a structural FEA. This FEA is performed with the meshed contact elements and the capsule. The loading and boundary conditions applied to the soft parts are the same as within the application case defined by the user ($\mathbf{F}_m = \mathbf{F}$). The transmission of the load between the contact parts is done through the capsule.

Get stresses σ_{hyd} and σ_{VM} . During joint morphogenesis, the hydrostatic and the von Mises stresses are the ones that influence the most on the cartilage growth [9]. Therefore, it is necessary to obtain the morphogenesis parts' stress distribution in the bioinspired methodology. From the results of the structural FEA, the σ_{hyd} and σ_{VM} stress fields are calculated.

Set growth potential β . The processes related to joint morphogenesis occur mostly at the epiphyses of the bones (distal and proximal portions of the long bones which joints with the adjacent bones). Nature sets the epiphyses' size based mainly on bio-molecular factors, which inhibit or promote certain cellular processes, depending also on the stage and type of cell. Within the bioinspired algorithm, this aspect is reproduced by the parameter named as growth potential β . By means of this parameter, the region where the morphogenesis parts are allowed to grow is defined. This region is where more matter can be added (malleable zone in Fig. 2). The growth potential can take value from 0 to 1, being 0 at the non-malleable zone and 1 at the malleable zone:

$$\beta = \begin{cases} 1 & \text{if } \text{abs}(y) \leq \lambda \cdot a \\ 0 & \text{if } \text{abs}(y) > \lambda \cdot a \end{cases} \quad (2)$$

The size of the malleable zone is defined λ times proportional to a geometrical characteristic of the initial geometry: the halfwidth a (Figure 2). The depth along the symmetrical axis of the parts is named y . The transition of the growth potential between the malleable zone and the non-malleable zone was smoothed.

Set growth factor Gf . In nature, cellular processes are regulated by growth factors, which are substances that act as signalling between cells. These signals (molecules) are produced by the cells in order to communicate to their

neighbour peers the stimuli they are sensing. When a cell receives these signals, a chain of events is triggered, including the amplifying of the signal and cell processes, among which, cell proliferation. Through the biological joint morphogenesis, cartilage cells express growth factors to signal the mechanical (hydrostatic and von Mises stresses) and bio-molecular stimuli. This process regulates how cartilage cells should proliferate. This aspect was included in the algorithm by calculating a term named growth factor, Gf . This factor depends on the hydrostatic stress, σ_{hyd} ; the von Mises stress, σ_{VM} ; the stress limit, σ_{lim} ; and the growth potential, β . The stress limit, σ_{lim} , which inhibits cartilage growth, was used as a switch in the algorithm. A limit value of $\sigma_{lim} = 0.5 \cdot \sigma_{max}$ was defined, where σ_{max} corresponds to the maximum von Mises stress within the malleable zone. The growth factor, Gf , was calculated as follows:

$$Gf = \begin{cases} \beta \cdot \sigma_{hyd} & \text{if } \sigma_{hyd} < 0 \ \& \ \sigma_{VM} < \sigma_{lim} \\ 0 & \text{in other cases} \end{cases} \quad (3)$$

Set growth coefficient α_i . Nature regulates tissue growth either by cell hypertrophy, cell proliferation or a combination of both. During joint morphogenesis, proliferation is the predominant mechanism. Cell proliferation rate is the factor that influences the tissue proportions (as well as the orientation of the cell division). The proliferation rate depends on the type of cell and its current stage. This effect within the bioinspired algorithm is represented by a growth coefficient, α_i . This term was defined as evolving linearly from a high growth coefficient (highly proliferative), α_{ini} , to a null growth coefficient (non-proliferative), with each step:

$$\alpha_i = \alpha_{ini} \left(\frac{1-i}{N-1} + 1 \right) \quad (4)$$

where i is the current growth step, and N is the total number of growing steps.

Isotropic growth FEA (addition of new matter). The growth can be modelled through the isotropic expansion of elements [12]. This effect can be simulated as a thermal expansion using FEA; being the thermal coefficient equivalent to the growth coefficient, α_i , and the temperature to the growth factor, Gf . Due to the thermal expansion, the morphogenesis parts get deformed. The volume variation is considered as addition of new matter, and the deformed state is set as stress-free (stresses are reset). With the obtained geometry a new capsule is generated with Boolean operations.

Contact performance assessment FEA (application context). With the new geometry, a contact FEA is carried out in order to assess the evolution of contact performance. Load transmission between parts is considered by means of direct dry contact. The peak contact pressure is evaluated as a performance variable.

Convergence test. At this stage, it is evaluated if the number of growth steps is reached.

4. Results

The proposed bioinspired methodology for the generative design of contact surfaces was tested in a design case of a unilateral contact joint. A case of two steel ($E=200$ GPa and $\nu=0.3$) cylindrical parts in contact was considered. The application case was treated as an axisymmetric model. A static force \mathbf{F} of magnitude 160 N was applied perpendicular to the upper surface of the top part, as represented in Fig. 2.a. The top part was only allowed to move vertically. The nodes of the lower surface of the bottom part were only allowed to move laterally, while all displacements of the centre node of the same surface were constrained. The diameter of the parts ($2a$) was defined as the same for both and equal to 5 mm. The height of both parts was defined high enough to prevent the boundary conditions from affecting the stress distribution on the contact surfaces. The height of the malleable zone was defined by $\lambda=1$. The initial geometry of the contact surface of the top part was defined by an ellipsoidal face (major radius: 2.50 mm, minor radius: 0.75 mm). The initial geometry of the contact surface of the bottom part was defined by a horizontal planar face. The peak contact pressure was chosen as a monitoring variable to evaluate the load transmission performance during the bioinspired shaping process. A convergence analysis allowed to define an optimal mesh size of 9E-3 mm. The results obtained in the first iteration were successfully compared with the theoretical Hertzian solution. The bioinspired algorithm was implemented using the programming language Python and the FEA software Salome-Meca and Code-Aster. Each iteration (growth step) lasted around 40 min on a standard laptop (64-bit i7 processor @ 2.7 GHz, 16 GB RAM, Ubuntu 18.04 operating system). The number of iterations was set up manually here to 20. For that number of iterations, a stabilization of the monitored variable (peak contact pressure) was ensured.

The results of the simulation are presented in Fig. 4. The evolution of the peak contact pressure is plotted in function of the growth step. In Fig. 4, the shaped contact geometry is presented in blue colour after (a) 4 growth steps, (b) 8 growth steps, (c) 11 growth steps and (d) 20 growth steps. In those figures, the initial geometry is represented by a grey shaded region to show clearer the new matter added by the algorithm. The adjustment of the contact geometry improves the load distribution which results in a 57% reduction of the maximum contact pressure compared to its

initial value. It is important to remark that the bioinspired joint shaping algorithm adds matter around the contact zone, increasing the contact area and gradually decreasing the contact pressure. At the end of the bioinspired morphogenesis process, the geometry is more conformal than that at the beginning. The von Mises and hydrostatic stress distributions are presented in Fig. 5 (a) and (b) respectively, for the initial and the final geometry. A reduction of about 80.4% and 81.4% of the maximum von Mises and hydrostatic stresses, respectively, was achieved. These results demonstrate that the shaping of the geometry, thanks to the bioinspired growing rules, allows a better stress distribution.

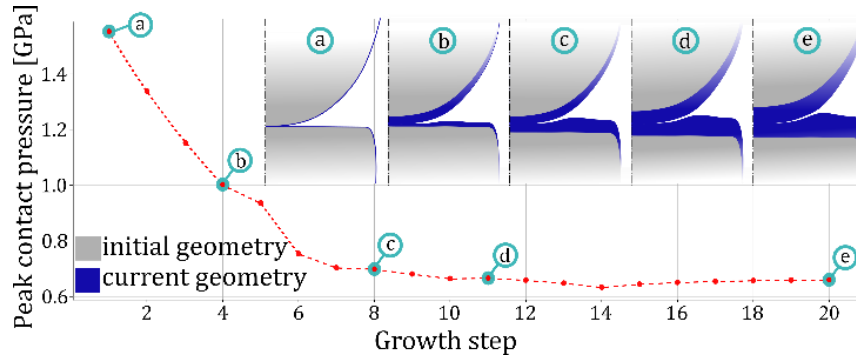


Figure 4. Evolution of the peak contact pressure and evolution of the generative geometry after: (a) initial configuration, (b) 4 growth steps, (c) 8 growth steps, (d) 11 growth steps and (e) 20 growth steps. For (a), (b), (c), (d) and (e) the aspect ratio vertical/horizontal was set equal to 4.

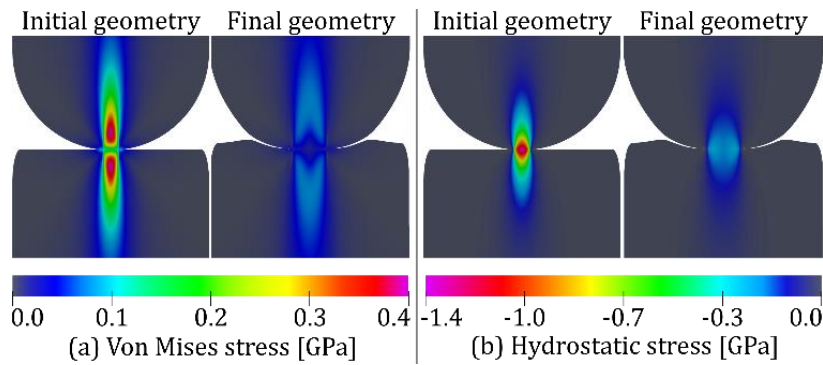


Figure 5. (a) von Mises stress and (b) hydrostatic stress distribution for the initial geometry and the final geometry for the case of a unilateral contact problem. Aspect ratio vertical/horizontal was set equal to 4.

5. Conclusion

Knowledge about biological joint morphogenesis opens new perspectives in mechanics to automate joint contact surface design. A mechanical transcription of cartilage growth rules was proposed and implemented to automatically shape contact surfaces. This work is a proof-of-concept demonstration about a generative design method inspired by biological morphogenesis. It demonstrates that the automated design of contact surfaces is feasible by mimicking cartilage growth and ossification.

The results obtained in this work are encouraging and can be of interest in mechanical design. A better distribution of the contact stresses (lower peak contact pressure) in mechanical joints means lower potential wear and therefore more durable systems. Another potential application of this work is custom prosthesis contact surfaces shaping, in which the real joint forces of the subject are considered during the design process.

It must be noted that the algorithm, as presented, is sensitive to the initial geometry, which now is user defined. For future work, the starting point of the algorithm might be defined as a function of the design constraints (loads and material properties). Additionally, the algorithm simplifies some biological processes such as the ossification. Nevertheless, future work will enable local changes in material properties by mimicking local ossification (as in bone development). This would allow also to explore alternative ways to define the convergence of the algorithm.

The work proposed in this article focuses on the genesis of joint surfaces. Prospects of development of this method would be to consider complementary biological processes, such as bone remodelling and self-repairing properties. This work is a step toward a computed-automated methodology for shaping functional mechanical parts.

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