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A COMPUTATIONAL MODEL OF 3D PRINTING ORTHOSES ASSOCIATED WITH A SYSTEMATIC STRUCTURAL ANALYSIS TOWARD REVERSE ENGINEERING ORIENTED PRODUCTION

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Abstract. *According to the recent advancement of the 3D printing technology coupling with CAD designs, a kind of reverse engineering production is getting in touch with reality in the field of assistive device production, which has been relying on expert prosthetists. It provides a large benefit not only for saving costs and time, but also offers a novel solution in senses of designs and materials beyond past knowledge. The computational framework is expected to enhance and accelerate a PDCA cycle of the production, which consists of the determination of the base design (Plan), CAD design with a specific parameter (Do), virtual and physical tests (Check) and improvements associated with the target specification for a subject (Act). In this study, we established such a PDCA framework with virtual and physical tests by using a skeleton computational model designed by the computer algorithm to be able to generate the 3D structure automatically. Focusing on a supportive device in flexing and extending of human knees, a compliant mechanism-inspired design was introduced and validated in the resistance of tensile loading forces, which was assumed to be knee extension. Depending on principle parameters in the skeleton design, the model was successfully transformed to the printable 3D structure, verified in the FEM structural analysis and examined in the physical test with a robotic tool to mimic the human knee motion. This complementary approach to binding virtual and physical validations will open a new door for the reverse engineering production of orthoses beyond projects currently being worked based on try-and-error 3D printing production.*

Keywords: 3D printing, Computational geometry, Compliant mechanism, Finite element model (FEM), Reverse engineering production, Human knee supportive device

1. Introduction.

The recent 3D printing advancement provides a large impact on production and soft robotics [1]. Originally, CAD/CAM software designs have a long history in engineering fields, providing enormous benefits in mass production. The recent highlight is availability of 3D printing for small-lot production and prototyping [2, 3]. In prosthetics and orthotics manufacturing, prosthetists normally take responsibility for its design and fabrication under prescriptions by medical doctors, which includes steps of body-part measurement, molding for fabrication, assembling of parts and adjustment to the target body part [4]. Since expert knowledge and techniques have supported the manufacturing process in a comprehensive view, the reverse engineering production cannot be reconstructed if it is a partial replacement of the steps to a mechanical method.

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Empirical approaches have been tried toward the establishment of reverse engineering in prosthetics and orthotics [5-16]. In the early stage, the concept design of the reverse engineering orthosis was presented by Teng et al. [5], while their device was too simple to reconstruct realistic orthoses. The workflow of CAD/CAM orthoses design was discussed by Weiss et al. [10] and Santos et al. [11], while it was still a simple and partial replacement of the fabrication process to reduce the burden of prosthetists without an automated adjustment and structural analysis. Recently, those pioneering works were evolved to parametric formulations to describe target models [13, 16]. Finally, an inevitable remaining problem is an integrated scheme with systematic verifications in senses of structural analyses [17, 18] and strength evaluation [19, 20].

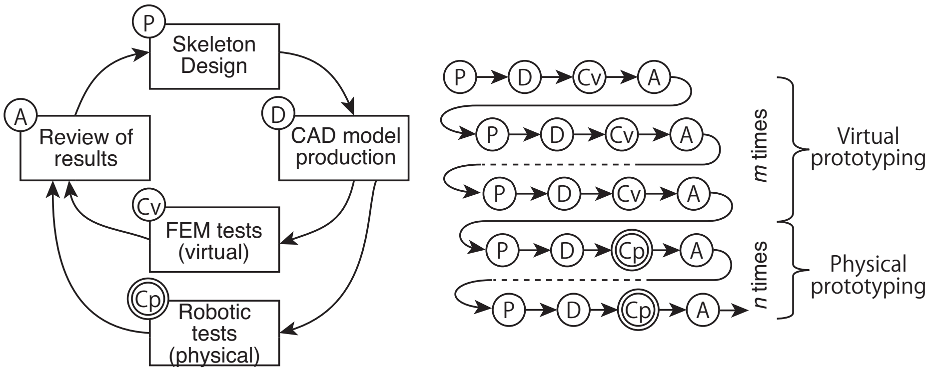
In parallel to past works discussed above, a challenging and remarkable approach is to introduce the essence of compliant mechanisms [21] for the orthoses design [22-30]. Compliant mechanisms can provide an arbitrary flexible mechanism with a specific force and motion transmission in accordance with elastic body deformation. Since they can be formed in a monolithic and jointless way, compliant mechanisms are a good match for the 3D printing method. In consideration of possible integration of the reverse engineering orthosis with compliant mechanisms, it may open a new door to provide 3D printing orthosis designs by using flexible fibers and the distribution of strength can be finely controlled depending on body-part segments in principle. In addition, a risk-free mechanism is required for human assist devices to prevent unnecessary overload in the joint motion, which may occur in embedded motor systems. Racu and Doroftei [28, 29] proposed to use a compliant mechanism for the ankle rehabilitation device as a safety technique, which provides comfort and keeps the patient's foot safe during the joint motion. Those facts imply that a compliant mechanism is beneficial for human assist devices not only for assistive mechanisms but also for safety techniques. However, compliant mechanisms have a large variety of designs, and then expert knowledge and decision-making are required to avoid a combinatorial explosion of parameters. It seriously undermines the interests of the challenging approach. In this study, for taking the first step toward the solution of this complex problem, we proposed a consistent framework coupling with an automated generation of the compliant mechanism design, which converts from the skeleton model with a few parameters to a detailed three dimensional one according to the upstream design concept [31].

The remainder of this paper is organized as follows. After giving the research background in Section 1, the necessary 3D printing orthoses was discussed in Section 2 and the proposed framework was described in Section 3. Section 4 showed results of the proposed approach, which was followed by conclusion in Section 5.

2. An Effective Framework for 3D Printing Orthoses.

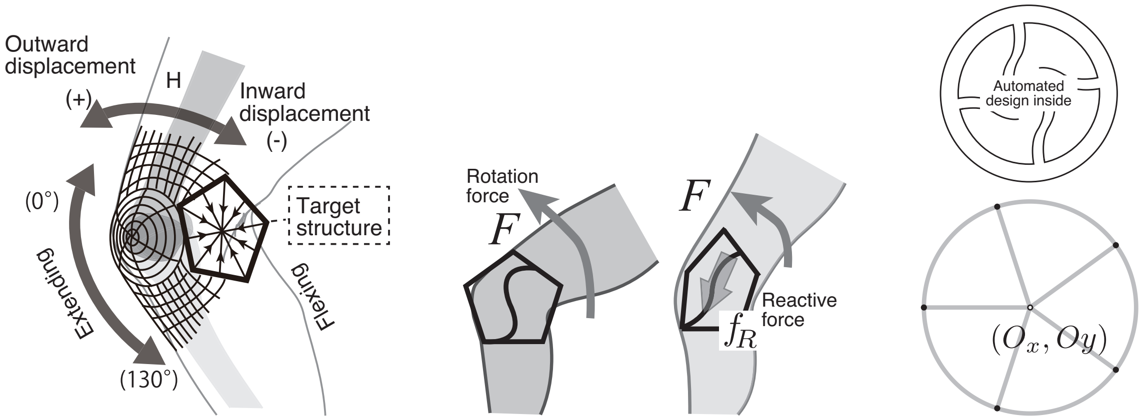
There is no doubt that 3D printing technologies contribute to rapid prototyping, while the reduction of necessary cost and time is inevitable in a paid production. A possible option is to reduce the number of cycles for the completion of prototyping, which is usually accompanied with physical tests and a simulation-based analysis to guarantee the target specification. Therefore, an important mission is to shorten the whole process effectively (Figure 1). For the realization of this concept, a systematic computational model is required due to the existence of a large number of parameters in the actual design specification. By separating parameters to be major variables to modify for the whole design and minor parameters as fixed sets, the upstream design can be derived [31]. Therefore, the necessary components for effective PDCA cycles for 3D printing are given as follows:

(i) a computational model to be able to classify upstream and downstream parameters,
(ii) availability of a numerical simulation for the structural analysis to be able to execute quick comparative tests, and



(A) (B)

Figure 1. A PDCA framework with virtual and physical tests to minimize costs and time for 3D printing orthoses



(A) (B) (C)

Figure 2. Knee movements (A), compliant mechanism to generate the resist force (B) and upstream design (C) for the 3D printing orthosis

(iii) a physical-test platform to be able to reconstruct easily depending on the requirement.

In this case, we assumed that the target design has a plate structure to support knee flexing and extending attached along the sides as shown in Figure 2(A), which is a simple and demonstrative example for the current purpose to highlight the separation of upstream and downstream designs. In consideration of compliant mechanisms to enhance a fusion effect of soft materials and the power of the design, we proposed a folding paper-inspired design, known as Origami in Japan, and introduced in a form of the computational model. A repetitive folding structure can be replaced to be parts of punching holes in the grid design. Figure 2(B) showed a schematic illustration of how a 3D printable compliant mechanism works to resist knee extension for patients with joint problems. As shown in Figure 2(C), a simple 2D structure based on the Origami-inspired design can provide an automated design with principal parameters on the outer form and the modifiable number of nodes for bridging beams to the center position (O_x, O_y).

3. Proposed Methods Implemented into the PDCA Framework.

3.1. **A skeleton model to be converted to the 3D model computationally.** According to the hypothesis, described in Section 2 about the components for effective PDCA cycles, the skeleton model was introduced with upstream parameters of the number of nodes N and the center position (O_x, O_y). The design was systematically generated with variables N and O_y by using **Algorithm** described below. Figure 3 showed the process of

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Algorithm  Automatic generation of the compliant mechanism orthosis part
Initialize fixed parameters to define the outer form and internal beams as follows:
  • the width of the outer form and beams as $W_d$,
  • the size as the diameter of the outer form (ring) as $L$,
  • $y$-coordinate of the center position as $O_y$,
  • the minimum and maximum $x$-coordinate of the center position as $O_x^{\min}$ and $O_x^{\max}$,
  • the minimum and maximum number of beams as $N_B^{\min}$ and $N_B^{\max}$.
for $N_B = N_B^{\min}$ to $N_B^{\max}$:
    for $O_x = O_x^{\min}$ to $O_x^{\max}$ with the step $O_x^{step}$:
    (I) Divide the $C^1$ circle as $[0, 2\pi]$ by $N_B$ in an equivalent way.
  • Compute nodes with angles $k \cdot 2\pi/N_B + \pi/N_B,\ k = \{0, \dots, N_B - 1\}$ in the circle.
  • Iterate with $k$ from 0 to $N_B - 1$ to generate each beam to connect the node and the
    center position $(O_x, O_y)$ as a skeleton line.
    (II) Provide edge lines of the beam as sides of each skeleton line.
  • Find crossing points of all generated lines.
  • Chop down unnecessary line terminals outside of surfaces of beams and the ring by
    using the plane sweep algorithm in the computational geometry.
    (III) Output lines to form all surfaces of the design (polylines in the DXF format).
    end for $O_x$
end for $N_B$
(IV) Convert the 2D DXF file to a 3D structure by adding the thickness in $z$-axis.
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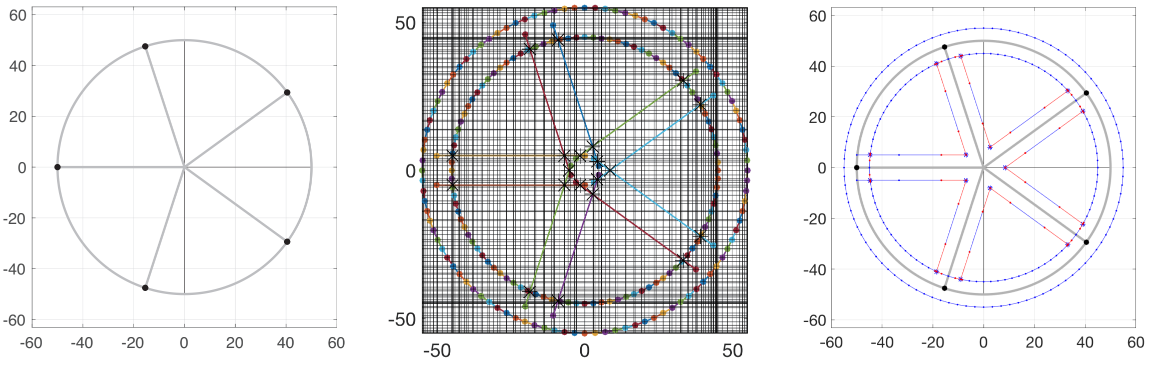


(A) A skeleton model

(B) Connecting beams

(C) Resultant 2D structure

Figure 3. (color online) A computational model to generate the 2D structure from the skeleton model by using Algorithm

generating the skeleton model and transforming the 2D design, which is easily upgraded to the 3D model by adding an appropriate thickness in z-axis. For the conversion from lines in the skeleton model to band with a given width W_d, a method of the computational geometry was applied to finding crossing points of lines to extract the right parts of the 2D model (Figure 3(B)), which were represented as red lines in Figure 3(C).

3.2. **A virtual FEM-based analysis.** Indeed, there is a wide variety of tools for the structural analysis used for design optimization [32], which are provided commercially [33] and in an open-source [34]. In this case, we demonstrated that the STL file was converted from the 2D model and they can be investigated seamlessly in the structural analysis with MATLAB FEM toolboxes [35].

3.3. **A physical and automated experiment with robotic devices.** For physical tests, the artificial knee testing system was designed with a programmable actuator with displacement, velocity torque sensors to reproduce motions of the knee as flexing and extending (Figure 4). By using the programmable actuator, the 2D plate-based orthosis part was examined, and necessary forces with respect to the displacement were automatically recorded in the system. The automated experiment provides an arbitrary number of test trials, which offers quantitative validation. It easily extends to a complex procedure composed of sets of motions as the designer needs to test, without any human manipulation after the settlement of the orthosis part in the evaluation system.

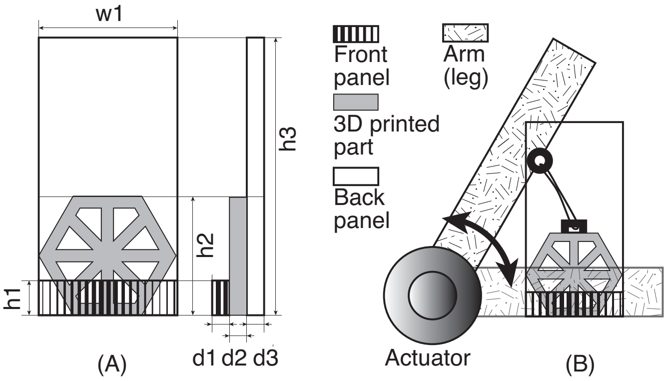
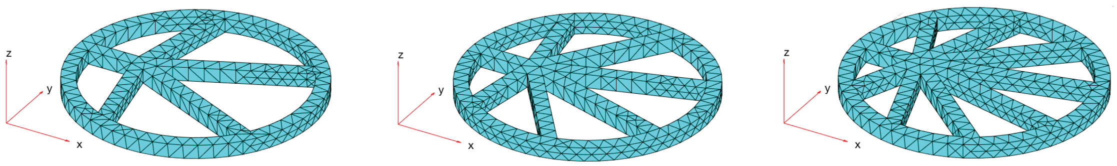


Figure 4. The proposed physical test environment provided by a smart actuator with displacement, velocity and torque sensors inside

4. **Results.** Results were obtained from FEM analyses in a virtual manner and robotic examination analyses in a physical manner.

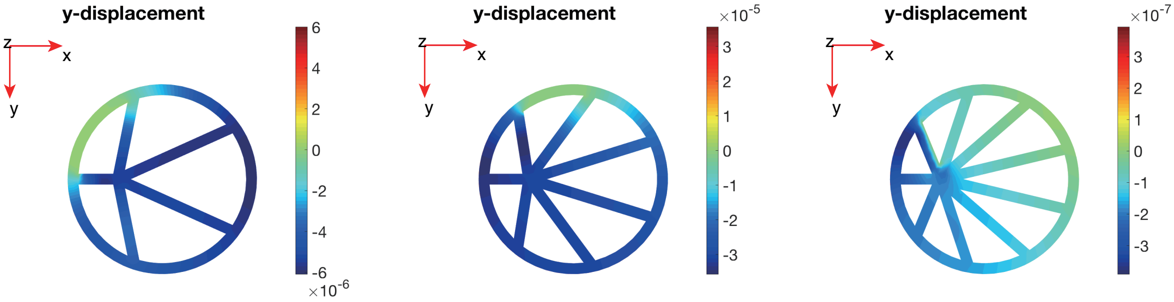
4.1. **FEM analyses.** We examined the prototype analysis by using the FEM toolbox and STL files were successfully derived by the conversion from the skeleton model automatically generated in the proposed algorithm, and they were systematically analyzed by the MATLAB code in an automated manner as shown in Figure 5. The programming code can compare the results from different designs. Depending on the number of bridging beams that connect to the center, displacement analyses clearly visualized the difference (Figure 6). Originally, the circular compliant mechanism requires human expert CAD manipulations with undecided parameters of $N_b \times 4$ to draw the target DXF file except the definition of **O** and N_b as principle parameters, which prevent an automated design procedure.



(A) 5 beams (B) 7 beams (C) 9 beams

Figure 5. Generated STL data for 3D printing with mesh information

By using the proposed algorithm, the systematic generation of the DXF files to draw the circular compliant mechanism were realized and it works in the given parameter range without human manipulations, which significantly reduces the development time in **P** and **D** processes in the PDCA cycle (Figure 1). It provides a smooth structure comparison in **C** and **A** processes in the cycle by the reduction of waiting time in repetitive cycles.

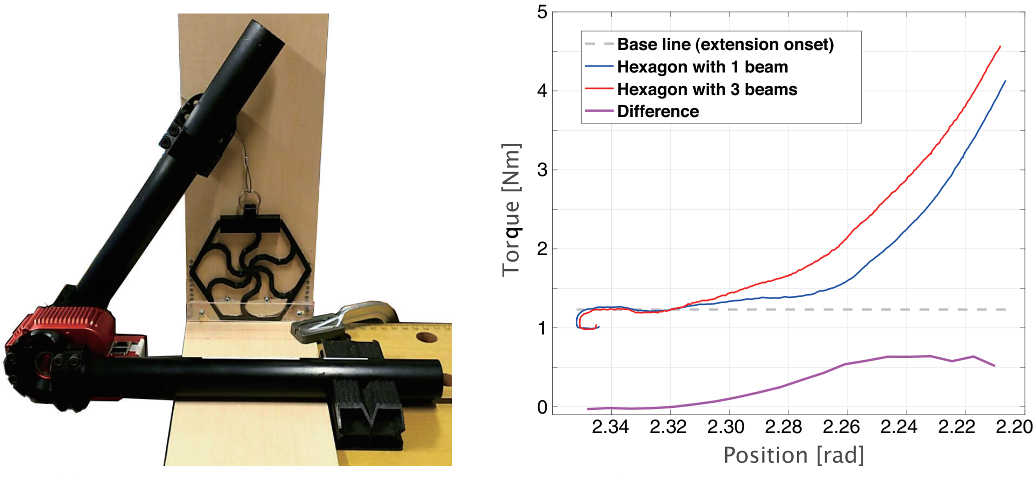


(A) 5 beams (B) 7 beams (C) 9 beams

Figure 6. (color online) A systematic displacement analysis of different designs by using the MATLAB FEM toolbox for the comparison

Therefore, the algorithm allows more flexibility in defining and analyzing the parameters and therefore is more suitable for comparing the different variations with one another for selecting the optimal result.

4.2. **Robotic experiments.** The X-Series actuator of HEBI Robotics [36] was introduced to reproduce the motion of the knee as flexing and extending (Figure 7(A)). The actuator with embedded sensors enables simultaneous control of displacement, velocity, and torque as well as three-axis inertial measurement and records of the values as temporal sequences every 10 [ms]. Temporal sequences of position (angle of the rotation), velocity and torque were observed and recorded by the actuator and the accumulated data can be analyzed for systematic comparison. Figure 7(B) showed a comparison between data obtained from different designs, which are hexagonal outer forms with the single wavy beam and three wavy beams as compliant mechanisms. In the evaluation system, the resist force was observed against the tensile loading motion, differently depending on the design (Figure 7(B)). Resist forces increased due to the rotation of the motion and the force difference was saturated from the midpoint, which implies that the kinetic difference of them was 1 [Nm] as the observed value. The result indicated that the resist force can be varied depending on the number of beams and the design can easily be modified to adjust the target value of the resist force.



(A) The artificial knee system (B) The resist force comparison

Figure 7. The robotic system for the physical test and results of the resist force comparison for 3D printing orthosis parts

5. **Conclusion.** In this study, we established such a PDCA framework with virtual and physical tests by using a skeleton computational model designed by the computer algorithm to be able to generate the 3D structure automatically, which provides a solution to solve past unsolved problems related to the reverse engineering oriented production. Focusing on a supportive device in flexing and extending of the human knee, a compliant mechanism-inspired design was newly introduced and validated in the resistance of tensile loading forces, which was assumed to be knee extension. Depending on principle parameters of the skeleton design, as an upstream design concept, the model was successfully transformed to the printable 3D structure, verified in the FEM structural analysis and examined by the physical test with a robotic tool to mimic the human knee motion. The results obtained from virtual and physical tests become feedback to enhance the PDCA cycle for the improvement of parameters in the next cycle effectively. This result clearly demonstrated the effectiveness of our proposal.

In the further development, this approach will be implemented for a model that accounts not only for the tensile loading during the knee extension as demonstrated here, but also the flexing action. An analysis of the stress concentration in a single beam may provide an advanced compliance mechanism design to be able to realize an effective force dispersion to reduce load of the body when flexing of the human knee joint. In this sense, the reverse engineering method allows adaptive designs to fit for actual requirements and needs of patients with knee problems and provides an opportunity for customization of the supportive device for a wide variety of situations and necessities in human joint problems.

This complementary approach to binding virtual and physical validations will open a new door for the reverse engineering production of orthoses beyond traditional approaches with try-and-error 3D printing production or human manipulations based on expert knowledge and skills.

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