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Research Article

Flexible Bar Geometric Designs for Personalized Knee Orthoses Inspired by Compliant Mechanisms

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ABSTRACT

Recently, 3D printed compliant mechanisms have been expected not only in engineering purposes, but also in supportive devices of human motions especially for human joint problems. On the other hand, the establishment of a systematic design principle is the issue to provide an actual solution for the target body problem, i.e. the personalization. In the present study, we proposed a systematic method to design flexible bars to reduce the burden of the human joint. The proposed concept was verified in computational analyses and the 3D printer productions were demonstrated in an actual implementation as prototypes. In computational analyses, larger deformations of the bars were analyzed to absorb the stress occurring a flexing action in joint's motion. Theoretical analysis and experiments were demonstrated its flexibility and support functions during the flexion and extension of the knee motion. It indicates that high importance of the geometrical analysis of the orthosis design in the sense of compliant mechanisms.

1. Introduction

3D printing methodology is getting to be extended in various types of additive manufacturing in research perspectives and applications. According to those developments, models in the prototyping stage can directly be tested in the actual field as 3D functional parts. In this sense, additive manufacturing has been widely adopted in industries from engineering purposes such as space engineering and automotive to medical purposes and arts. With respect to the conventional technology, the production process is a high flexibility of the geometry to maximize the desired function. The mass production is outdated currently, and a high-mix low-volume production is expected. The concept of compliant mechanisms is suitable for such a direction, which significantly reduces the number of parts to assemble and solve complex maintenance issues and allows to provide a simple fabrication and realize an ideal deformation to execute the target motion.

Thus, a controllable elasticity in the repetitive cycle motion can be derived from those compliant mechanisms replying on the geometry and the infill density, and pattern. According to the unique property, compliant mechanisms can be assured candidates for orthotic devices applications. The 3D printing compatibility of them allows a fine customization with respect to requirements in individual patients.

The rest of this article is structured as follows: Section 2 gives the research background, the methodology for developing various the designs is described in Section 3, Section 4 explains and summarizes the results, Section 5 gives a discussion, Section 6 concludes the paper.

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2. Related Work: Compliant Mechanisms

In the viewpoint of flexible materials and its function, the topology was initially investigated in Murphy et al. (1996) [1], followed by the related study [2], which discussed the design of parallel-guiding mechanisms. Trease et al. (2005) [3] demonstrated a possibility of large displacement compliant joints, which is an important proposal of a revolute and a translational solution of joints with large range of motion. Jingjun et al. (2009) [4] designed a compliant building block for micro/nano positioning and related works [5], [6] and [7] presented the design and applications of spread type of compliant joint as a cross-spring pivot.

In addition, advancements of the compliant joints reached the compatibility of the 3D printing materials and their properties as an issue to be solved in the sense of potential functions of the mechanisms. The 3D printed structures have a property of deformations, which is derived from a flexible filament with varied relative density (infill) [8]. Xiao and Gao (2017) [9] discussed properties and functions in the medical use of TPU materials. In the orthopedics application of the 3D printing, orthotic device can be provided as demonstrated by Chen et al. (2020) [10] and Lin et al. [11] and [12]. Therefore, the methodology of designing for orthotic devices has further extended in the large medical and supportive system such as the result of Chaparro-Rico et al. (2021) [13].

3. Methodology

3.1. *Flexible Bars and 3D Printing Parameters*

Proposed beams were designed in Autodesk Inventor Professional 2021. In the first place, types were divided into four groups (A, B, C and D) associated with common geometrical features. For bars in Group A, the geometry was changed morphologically from a simple beam design annotated with 0. In bars in Groups B, C and D, the geometry was changed to add an additional beam part in forms of 1) a half regular polygon with different number of the sides, 2) square, 3) hexagon and 4) half circle respectively. All bars were designed with the same length l=160 [mm] and a square cross-section a=10 [mm]. Thus, the compliant hinging geometry was varied depending on the bars. Individual groups with all bar variations were shown in Figure 1. The dimensions of given groups were marked on the figure. Once a 3D printing was completed, the physical pretotypes of the bars can be attached laterally of the knee by implementing int a cloth bracket. Since the bars are designed to match certain requirements as compactness, the supportive function is expected to provide during the knee flexion and extension if the lateral stability of the knee joint is accursed.

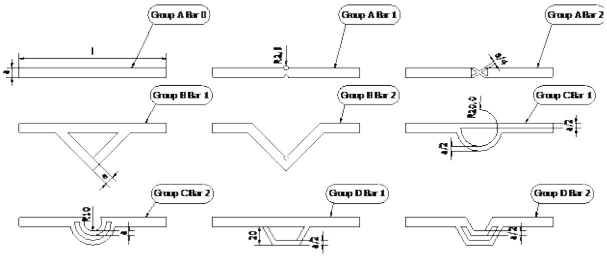


Fig. 1. Bar Groups

All bars were provided by using the Fused Deposition Modeling (FDM) technology on a 3D printer Anycubic i3 Mega with a flexible Thermoplastic Polyurethane (TPU) filament called Ninjaflex commercially [14]. The samples were printed under the same condition and parameter, as shown in Table 1. It shows configurations for the slicing software Ultimaker Cura. The orientation for a sample on the 3D printing platform is given in the same condition, which means that the models are flat with their surface in the platform. As shown in Table 1, the samples were printed with infill density of 90% and infill pattern known as Cross 3D, which was referred by the description of the slicing software Ultimaker Cura [15]. It suggests that it is a robust infill way for 3D deformations.

Therefore, the infill density percentage is highly important related to stiffness of the parts. In principle, the higher infill density, the stiffer the part is. On the other hand, when the infill density is getting to be high, the sample becomes heavier as shown in Figure 2. It shows that the time duration of the printing process grows linearly up to 90% and it increases significantly at a 100% at last. Therefore, 90% was selected for infill density in this study to avoid unnecessary processing time with a certain strength.

Table 1. 3D printing Processes

Parameter	Values
3D printer	Anycubic i3 Mega
Slicing Software	Ultimaker Cura
3D printing Material	Ninjatek Ninja Flex TPU Filament
Printing Temperature [°C]	230 (Recommend for the material)
Platform Temperature [°C]	60
Supporting Material	No
Infill Density[%]	90
Infill Type	Cross 3D
Layer Height [mm]	0.1
Printing Speed [mm/s]	30

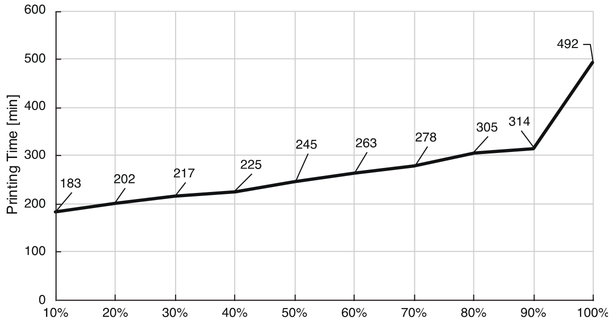


Fig. 2. Relationship between the 3D printing Infill Density and the Printing Duration

The processing time was shown in Figure 2, which was a case of Group A Bar 0 and other processing time have a similar tendency.

3.2. *Load Analysis of the Bars*

For sake of the lowest resistance when supporting the motion in the knee flexion, the bar is bending to provide a resistance force preventing lateral motion. The full range of motion of the human knee joint has to be considered to be ranging from fully extended knee as 0° degree to fully flexed knee at 140° degree. In this sense, the designed compliant beam needs to provide a deformation in the range. On the other hand, according to its symmetry, each side of the joint is required to deform at an angle of 70° approximately. In the analysis of the deformation, the samples were tested in non-linear environment by using Autodesk Inventor Nastran.
The models were illustrated in Figure 3, which represent with a schematic view of the loading conditions. The terminal points of the bars were fixed, and a given force was applied at the middle of the models.

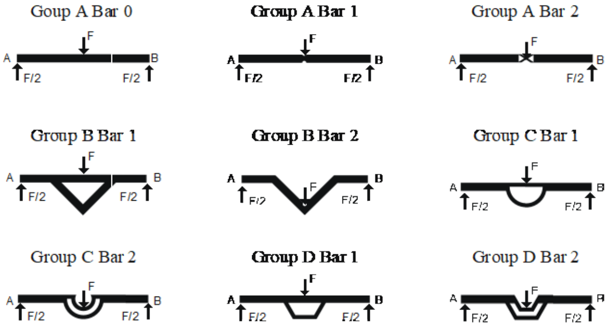
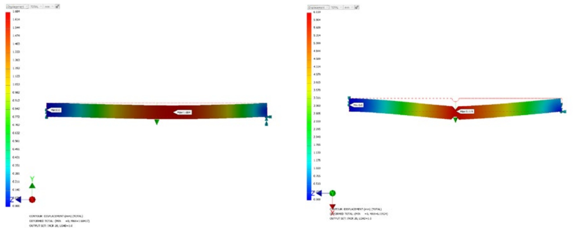


Fig. 3. Loads on the Bars

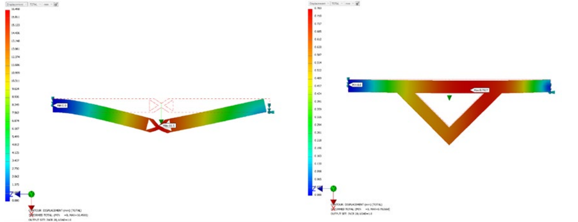
The results of the Finite Element Analysis (FEA) were demonstrated by individual deformations of the bars under the same set of boundary conditions. The beams having a property to exceed an enough level of the deformation are suitable for parts of knee assistive devices.

4. Results

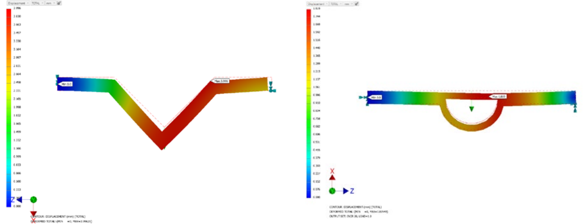
All beam models were analyzed in FEA in the non-linear static stress environment of Autodesk Inventor Nastran, where a 3-point bending test as shown in Figure 3. We focused on the large deformations in a non-linear elastic material. As shown in Figure 4, all beams were loaded with the force F=150 [N] in negative Y direction. The mechanical properties of the material were provided with the Ninjaflex TPU filament, which has Young's Modulus as 12 [MPa], Tensile Strength as 26 [MPa] and Poisons Ratio as 0.35. The computer experiment of each sample was done with 20 increments. In the present study, the highest deformation of each beam is the target phenomenon to investigate and how it works well in the same loading force, which changes depending on the geometry. The non-linearities contribute to large deformations of the model with the anisotropic material. Figure 4 showed the setup of the analysis and the results for all models.



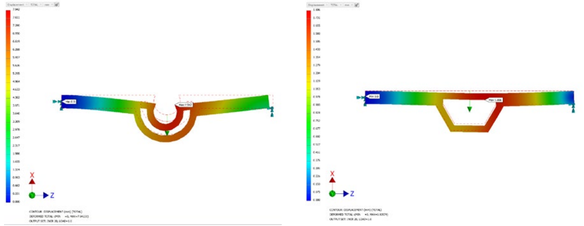
(a) Group A Bar 0 (b) Group A Bar 1



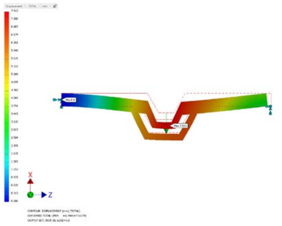
(c) Group A Bar 2 (d) Group B Bar 1



(e) Group B Bar 2 (f) Group C Bar 1



(g) Group C Bar 2 (h) Group D Bar 1



(i) Group D Bar 2

Fig. 4. Non-linear Static Stress Analysis of the Bars with the Largest Deformations

The values of the stress and the displacements were given in Table 2. In Figure 5, the stress and the displacements of the beams during the FEA bending test were presented, which the parameter values were arranged from the smallest to the largest.

Table 2. Mechanical Behavior of the Bars

Name	Stress σ_{Max} [MPa]	Displacements Δ [mm]
Group A Bar 0	33.75	1.684
Group A Bar 1	45.13	6.119
Group A Bar 2	62.73	16.5
Group B Bar 1	30.04	0.7827
Group B Bar 2	39.17	3.996
Group C Bar 1	34.47	1.819
Group C Bar 2	46.58	7.942
Group D Bar 1	35.37	1.806
Group D Bar 2	4.681	0.2599

As shown in Figure 5, the samples with highest values of the stress and the displacements were analyzed in cases of Group A bars 3, 2 and 4. Lowest values were found in samples from Group B as bars 1 and 3. Similarly, the displacements with highest values were observed in Group A Bar 2 and Group C Bar 2, the lowest was found in Group D bars 2.

As we expected, the highest deformations were observed in highest levels of the stress in the samples.

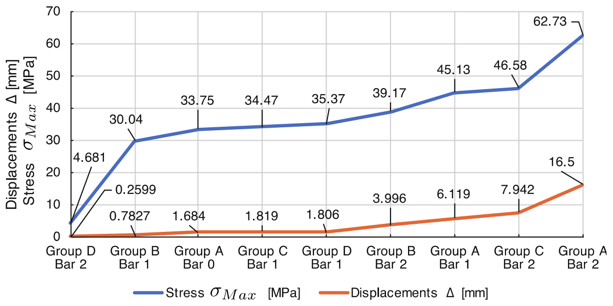


Fig. 5. Mechanical Behaviors of the Bars Based on the Geometry

In consideration of the applicability for an orthotic device, an appropriate balance of the stress and the strain (displacements) relationship is necessary. In this sense, possible candidates were Group A Bar 2 and Group C Bar 2 in the set of our designs.

In all beams, force-displacement relationships in simulation were shown in Figure 6, which imply non-linear behavior of the models. For some beams such as Group A Bar 0, Group B Bar 1 and Group D Bar 2, the load of 150 [N] was not significant enough to deform them out of the linear elastic region.

All 9 samples were provided by 3D printing with parameters in Table 1. The physical prototypes were made from TPU filament as shown in Figure 7.

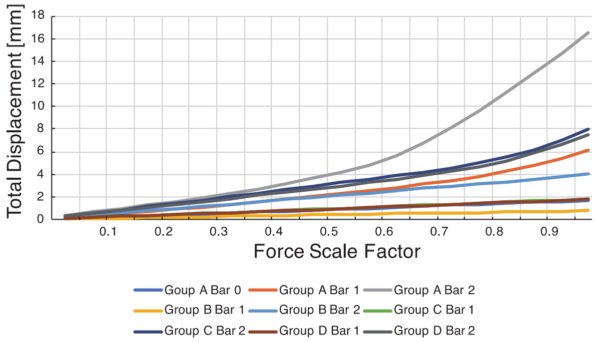


Fig. 6. Non-linear Deformation of the Bars – FEA Results

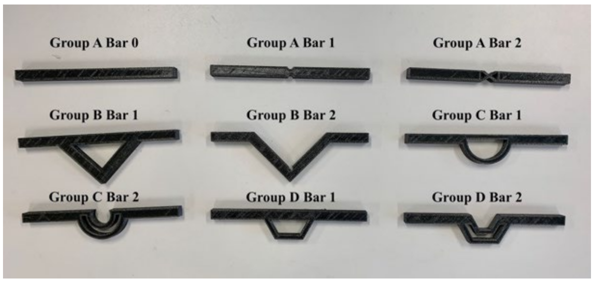
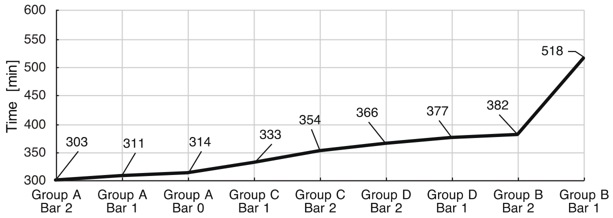
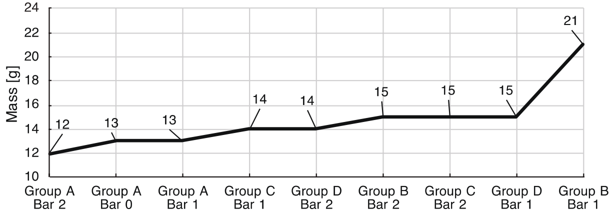


Fig. 7. Sample 3D printed from Flexible TPU Filament

The measured 3D printing time and the measured mass of the physical samples were respectively shown in Figure 8(a) and (b). Group B Bar 1 takes more 2 hours longer than the other samples. By focusing on compactness and low mass for an actual use as a lightweight attachment, the mass of the models is also important. Group B Bar 1 was the model with the highest mass as 21 [g], 6 [g]heavier than the next beam Group D Bar 1.



(a) 3D Printing Time of the Samples



(b) Mass of the 3D Printed Samples

Fig. 8. Duration of the 3D Printing and Mass of the Samples

In design and evaluation processes, all the parameters have to be carefully balanced. Table 3 showed a summary of all bars as the applicability criterion. The evaluation criteria were considered as high level of the displacements (high flexibility), low level of the stress, low duration of the printing process and mass of the prototype. These four parameters were labeled as G as "good", o as "average" and x as "poor" which respectively rated with points 1, 0 and -1 in this criterion panel. The result of the panel suggests the best beam suitable for the implementation into the compliant hinge of an orthotic device for the knee joint.

Table 3. Evaluation of the Samples

Name	Stress	Displacements	Time	Mass	Score
A 0	x	x	G	G	0
A 1	G	G	G	G	4
A 2	G	G	G	G	4
B 1	x	x	x	x	-4
B 2	o	o	x	o	-1
C 1	o	o	o	o	0
C 2	G	G	o	x	1
D 1	o	o	x	x	-2
D 2	x	x	o	o	-2

According to the criterion panel, Bars 1 and 2 from Group A and Bar 2 from Group C were the models with positive points and therefore those are appropriate for the task.

5. Discussion

In the present study, we investigated the potential of flexible compliant beams in the additive manufacturing in the field of orthopedics as a knee supportive device.

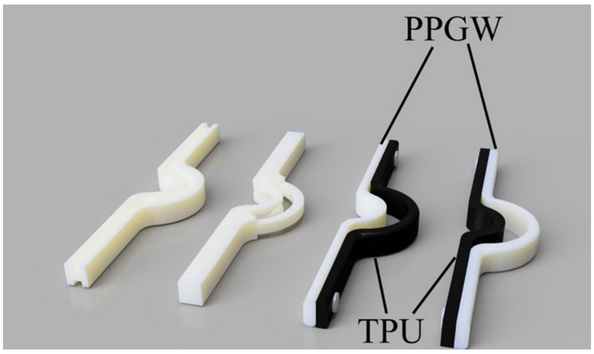
In order to achieve the purpose, 9 models were proposed and analyzed in non-linear FEA accounting for the large displacements. For more assured analysis, the results of computer simulations should be evaluated in comparison with data from physical tests from real materials, especially in the stress-displacement relationships if the models have flexible properties due to their geometries. The prototype support device was shown in Figure 9, which includes an extended behavior (a) and flexed behavior (b). In the sense of the three-dimensional deformation, an out-of-plane deformation has to be analyzed such as a lateral stability of the knee in this case. Those issues will be addressed in future missions. Interestingly, in the physical analysis, as shown in Figure 9, the out-of-plane stability of Bar 2 from Group C can be expected. There is a possibility of the extended design based on the hybrid style, by using a 3D printed part made from the PPGW material (Figure 10). It allows free motion in bending and stabilizes the joint motion during walking.


(a) (b)

Fig. 9. Physical Prototype Used in Orthotic Support

As part of the future plans, the lateral deformations need further improvements of models with larger resistances. A systematic idea to improve the lateral stiffness is shown on Figure 10 (a) by replacing the square cross-section with a "I-type beam" cross-section and increasing the range of motion is illustrated in (b). Figure 10 (c) and (d) represents a multi-material assembly of the beam combining a stiffer PPGW and TPU filament to provide a larger lateral stability and higher control over the stiffness.

Another unique opportunity can be provided by the additive processes and the infill density variability contributes to allow a local control of the stiffness of the model. A combination of those factors will open a further potential of the additive manufacturing for customizable solutions to fit for individual requirements.



(a) (b) (c) (d)

Fig. 10. 3D Representation of the Beam

6. Conclusion

The mechanical behavior of 3D printed flexible beams was analyzed with application as an orthotic device. The bars inspired by compliant mechanisms were verified in the required motion having hinging mechanisms. A non-linear FEA accounting for the anisotropic material and the large deformations of the flexible models were conducted on all beams to determine the most appropriate for the application. In analyses of 3D printing time and the mass of the samples, the criterion panel was clarified to rank scores to evaluate objectively how much a beam is appropriate for the applicability.

Advantages of proposed beams were the low-cost, low mass and compactness in comparison to traditional solutions such as mechanical parts. The simple and replaceable attachment has a large benefit for the implementation into support devices with different stiffness depending on rehabilitation stages of patients with joint problems.

According to the proposed method as the basement, the evaluation table will be extended including more parameters such as various cross-section geometries, infill patterns and densities and multi-material assemblies, which combine flexible and stiff materials in the design of supportive devices.

Capabilities of the additive manufacturing processes are constantly increasing, and 3D printing allows various fabrications in the wide range including complex geometries with turned stiffness for the target issue. It will extend an opportunity for realization of devices fit for individual personal requirements in the field of orthoses. It helps in strengthening the important link of the patient-doctor relationship aiming for improving the quality of life.

Acknowledgements

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Authors Introduction

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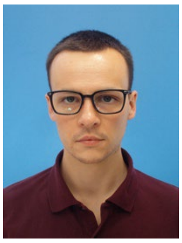

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