A Systematic Geometric Design Method of Flexible Bars Available for Personalized Knee Orthoses with Spring-Damper Functions

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Abstract

3D printed compliant mechanisms were recently highlighted not only in the traditional way, but also in the reverse engineering of human joint supportive devices. However, a systematic design principle is unclear for solving of the issue how it can be modifiable to fit to target body requirements in the sense of the personalization. We proposed a geometrical approach providing the target design by using a morphological replacement at the concentration of stress. This concept can be verified in orthoses to improve the knee joint function by 3D printed flexible prototypes. It allows larger deformations of the bars to control joint's motion. Theoretical analysis and experiments demonstrate the flexibility and support during the flexion and extension of the knee. It implies the impact of the geometry in orthosis design.

Keywords: 3D Printing, Flexible Bars, Compliant Mechanisms, Knee Supportive Orthoses, Customized Design

1. Introduction

The advancements in 3D Printing and Additive Manufacturing and the increased interest from a research perspective in the recent years have enabled their applications outside of the prototyping stage and directly into functional parts. Additive Manufacturing has been widely adopted in industries such as Space Engineering, Automotive, Medicine and Stomatology, Jewelry and Fashion, and more. Amongst its advantages in comparison with the conventional technological processes are the ability to control the geometry from inside and therefore the density of the structure and optimizing the mass to strength ratio of the part, realizing complex shapes, and avoiding entirely the assembly process, fabricating mechanisms that rely solely on deformation to execute the motion called compliant mechanisms.

These compliant mechanisms have controllable elasticity (depending on the geometry and the infill density, and pattern) and repetitive cycle motion. Those unique propertied make them strong candidate for orthotic devices applications. In addition, the 3D Printing compatibility of the compliant mechanisms allows deeper customization regarding the individual patient's requirements.

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.

2. Related Work

From a research perspective, compliant mechanisms are not new topic due to their capabilities and behavior. The topology is investigated in [1] and [2] gives the design of parallel-guiding mechanisms. [3] provides the design of large displacement compliant joints. This research works proposes a revolute and a translational solution of joints with large range of motion. In [4] a design based on compliant building block for micro/nano positioning is described. In [5], [6] and [7] the design and applications of more commonly spread type of compliant joint – a cross-spring pivot are analyzed.

In addition to advancements in the compliant joints research, the compatibility of the 3D Printing materials and their properties is crucial to the proper function of the mechanisms. The deformations of 3D Printed structures made from a flexible filament with varied relative density (infill) are explained in [8]. In [9], the authors discuss the properties of the medical grade TPU. Other works show the application of the 3D Printing the Orthopedics for creating orthoses such as [10], [11] and [12]. The methodology of designing such orthotic devices for the human arm is provided in [13].

3. Methodology

3.1. *Flexible Bars and 3D Printing Parameters*

The beams are design in Autodesk Inventor Professional 2021. Initially, divided into four groups (A, B, C and D) based on common geometrical features. For the bars in Group A, geometry is removed from a simple beam annotated with 0. In Groups B, C and D, geometry is added to the beam as a half regular polygon with different number of the sides – square, hexagon and half circle respectively. All bars have same length l=160 mm and a square cross-section a=10 mm. The compliant hinging geometry is varied. Groups with all bar variations are shown on Figure 1. The dimensions that are unique for a given group are marked on the figure. Once 3D Printed, the physical pretotypes of the bars will be attached laterally of the knee. Therefore, the bars have to match certain requirements such as compactness, providing lateral stability of the knee joint and supporting the knee flexion and extension.

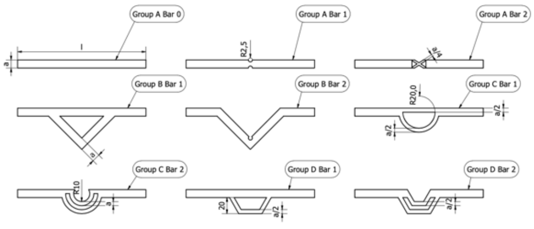

Fig. 1. Bar Groups

All bars are 3D Printed by using the Fused Deposition Modeling (FDM) technology on a 3D printer Anycubic i3 Mega from a flexible Thermoplastic Polyurethane (TPU) filament called Ninjaflex from the company Ninjatek [14]. The specimens are printed under the same conditions and by using the same settings (parameters) as shown in Table 1 configured in the slicing software Ultimaker Cura. The orientation for one of the specimens on the 3D Printing building platform is the same – the models are flat with their most surface in the platform. As shown in Table 1, the samples are printed with infill density of 90% and infill pattern called Cross 3D and according to the description of the slicing software Ultimaker Cura [15] it is a strong infill appropriate for 3D deformations.

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, ℃	230 (Recommend for the material)
Platform Temperature, ℃	60
Supporting Material	No
Infill Density, %	90
Infill Type	Cross 3D
Layer Height, mm	0.1
Printing Speed, mm/s	30

The infill density percentage is an important parameter related with stiffness of the parts. In general, the higher the infill density the stiffer the part is. However, it should
be noted that increasing the infill leads to heavier samples and interesting observation shown in Figure 2 is that the time duration of the printing process grows linearly up to 90% and then increases significantly at a 100%. Therefore, 90% was chosen for infill density across all samples.

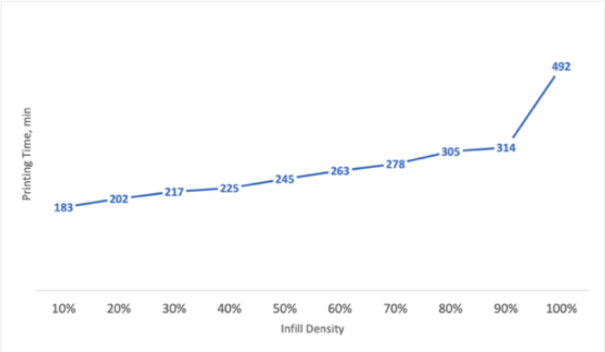

Fig. 2. Relationship between the 3D Printing Infill Density and the Printing Duration

The example shown on Figure 2 is for Group A Bar 0 but applies for all samples.

3.2. *Load Analysis of the Bars*

The main requirement of the beams is to provide the lowest resistance support the motion during knee flexion (in plane bending while at the same time preventing lateral (out of plane) motion. In addition, the full range of motion of the human knee joint must be considered as well – from fully extended knee – 0° to fully flexed knee at 140 ° degrees. The designed compliant beam must provide deformation in this range. However, due to its symmetry, each side of the joint need to deform at about an angle of 70°.
The samples have been tested in non-linear environment using Autodesk Inventor Nastran.
The models illustrated in Figure 3 represent a schematic view of the loading conditions. The members are fixed in one end and at the other a roller support is used. A force is applied at the middle of the models.

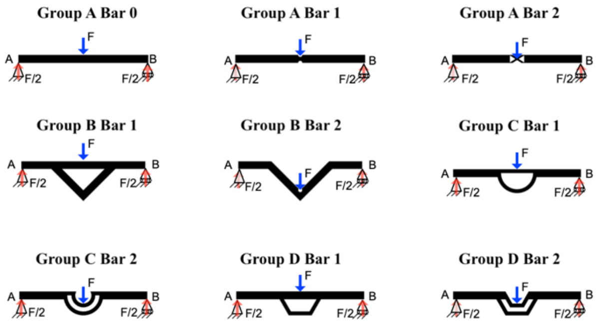

Fig. 3. Loads on the Bars

The results of the FEA analysis will show which bars deform the most under the same boundary conditions. The beams realizing the highest values of the deformations are suitable candidates as a knee assistive device.

4. Results

All beam models were subjected to a Finite Element Analysis in the Non-linear static stress environment of Autodesk Inventor Nastran where a 3-point bending test was conducted on the samples. The study accounts for the large deformations and uses a non-linear elastic material. All beams are loaded with the same force F=150 N in negative Y direction as shown on Figure 4. The mechanical properties of the material are based on the Ninjaflex TPU filament – Young's Modulus is 12 MPa, Tensile Strength 26 MPa and Poisons Ratio is 0.35. The simulation of each sample includes 20 increments. The purpose of this study is to show the beams with the highest deformations while the same loading is applied based on the geometry while accounting for the non-linearities from large deformations of the model and the anisotropic material. Figure 4 shows the setup of the analysis and the results for the models with highest displacements – Group A Bar 2 and Group C Bar 2 respectively.

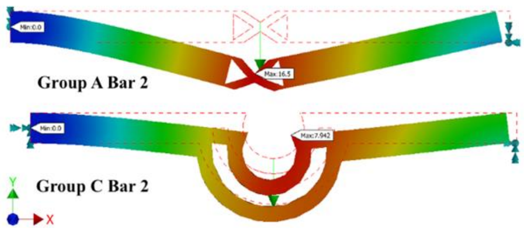

Fig. 4. Non-linear Static Stress Analysis of the Bars with the Largest Deformations

The values of the stress and the displacements from the studies are given in Table 2. The plots on Figure 5 summarize the results from the analysis for the stress and the displacements of the beams during the FEA bending test. The values are 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 it can be observed in Figure 5, the samples that experienced the highest values of the stress and the displacements are from Group A bars 3, 2 and 4. The lowest values belong to samples from Group B – bars 1 and 3. Similarly, the displacements with highest values are again members from Group A Bar 2 and Group C Bar 2 respectively and the lowest – Group D bars 2.
As it is expected, the highest deformations lead to the highest levels of the stress in the samples.

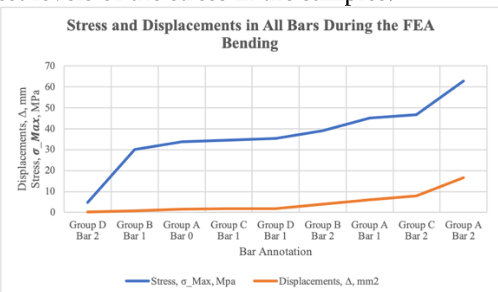

Fig. 5. Mechanical Behaviors of the Bars Based on the Geometry

For the samples to be applicable for an Orthotic device, a good balance of the stress and the strain (displacements) relationship is required. Therefore, possible candidates are Group A Bar 2 and Group C Bar 2.
The force-displacement relationships for all beams after the simulations are illustrated on Figure 6. The non-linear behavior of the models can be observed from the plots. 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.

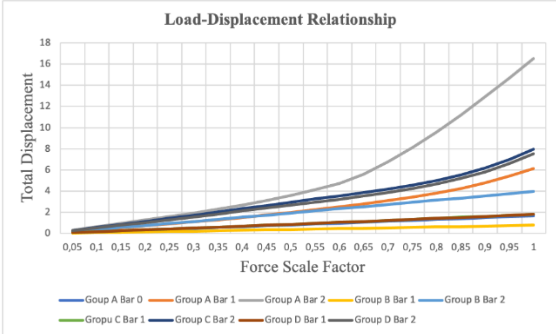

Fig. 6. Non-linear Deformation of the Bars – FEA Results

All 9 specimen were 3D Printed following the with the parameters from Table 1. The physical prototypes made from TPU filament are show on Figure 7.

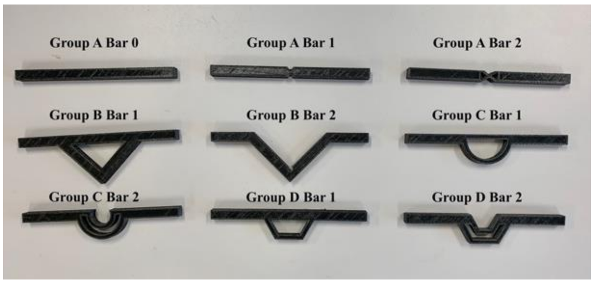

Fig. 7. Sample 3D Printed from Flexible TPU Filament

Figure 8 illustrates the measured 3D Printing time in minutes a) and the measured mass of the physical samples in grams b). It can be observed that Group B Bar 1 takes more 2 hours longer than the other samples.
Another important parameter is the mass of the models – due to their attachment laterally of the knee, compactness and low mass are required from the beams. Here again Group B Bar 1is the model with the highest mass – 21 grams, 6 grams heavier than the next beam Group D Bar 1.

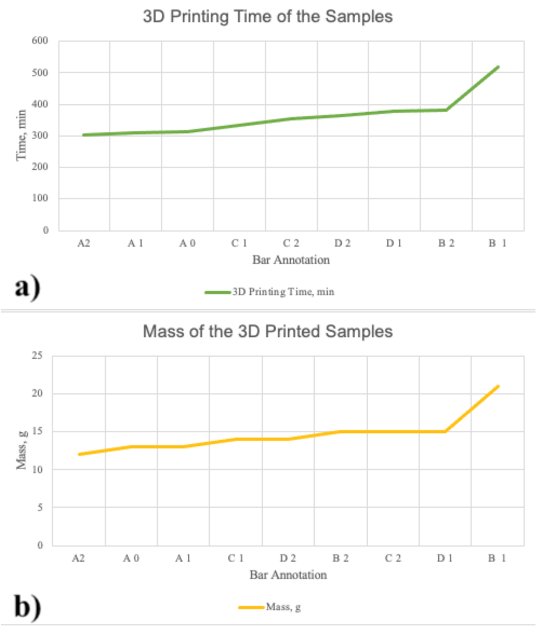

Figure 8: Duration of the 3D Printing and Mass of the Samples

In the process of designing and evaluating the level of applicability of the beams for the task, all of the above parameters have to be carefully balanced. This is reflected in the evaluation Table 3, created for all bars. The evaluation criteria are: 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 are labeled as "good", "average" and "poor" and rated with points 1, 0 and -q respectively. After that the points are combined and the beams with most points are the most suitable to be implemented as a compliant hinge of an orthotic device for the knee joint.

Table 3. Evaluation of the Samples

Name	Stress	Displacements	Time	Mass	Score
A 0	poor	poor	good	good	0
A 1	good	good	good	good	4
A 2	good	good	good	good	4
B 1	poor	poor	poor	poor	-4
B 2	avg.	avg.	poor	avg.	-1
C 1	avg.	avg.	avg.	avg.	0
C 2	good	good	avg.	poor	1
D 1	avg.	avg.	poor	poor	-2
D 2	poor	poor	avg.	avg.	-2

As it can be observed from the table, Bars 1 and 2 from Group A and Bar 2 from Group C are the models with most points and therefore most appropriate for the task.

5. Discussion

In this research we investigate the application of the flexible compliant beams fabricated by using the advancements in the Additive Manufacturing in the field of orthopedics as a knee supportive device.

In order to achieve that, 9 models were develop and analyzed in Non-linear studies accounting for the large displacements the supports have to undergo in a real working environment. However, the simulations are not used to provide precise values of the stress-displacement relationships but to limit the models with less flexible properties due to their geometry.

It is important to mention, the out of plane deformations that have to be eliminated to provide a lateral stability of the knee were not included in the FEA studies. They are subject to the future development of the models.

After the evaluation process of the samples, due to its better out of plane stability Bar 2 from Group C was implemented in such a device 3D Printed from a material PPGW. The prototype support is shown on Figure 9 a) extended and b) flexed knee. It allows free motion (bending) and stabilizes the joint during walking.

Fig. 9. Physical Prototype Used in Orthotic Support

As part of the future plans, the lateral deformations have to include in the studies and models that provide greater resistance will be developed.

Examples of improving the lateral stiffness is shown on Figure 10 a) by replacing the square cross-section with a "I" beam cross-section and increasing the range of motion is illustrated in b).

Another unique opportunity provided by the additive processes is the infill density variability allowing local control of the stiffness of the model.

Combining the above parameters will unlock the great potential of the additive manufacturing for customizable solutions depending on the individual requirements.

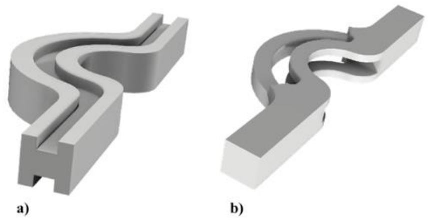

Fig. 10. 3D Representation of the Beam

6. Conclusion

This paper analyses the mechanical behavior of 3D Printed flexible beams with application as a orthotic device. The bars use their compliance to execute the motion and have different hinging mechanism. A non-linear finite element analysis accounting for the anisotropic material and the large deformations of the flexible models was conducted on all beams to determine the most appropriate for the application. In the selection process the 3D Prating time and the mass of the samples were included. Plots of the results were provided. An evaluation table ranking the criteria was created to objectively determine the beams with most applicable behavior.

Advantages of the designed beams are the low-cost, low mass and compactness in comparison to existing solutions that are hardly affordable and complicated. It allows for simple attachment and replacement with a support with different stiffness depending on the stage of the healing process of the patient.

In the future, this table will be extended including more parameters such as various cross-section geometries, infill patterns and densities and multi-material assemblies combining flexible and stiff materials in different areas of the supportive device.

The constantly increasing capabilities of the additive manufacturing processes and 3D Printing more specifically allow for fabricating complex geometries with controlled stiffness for the first time providing an opportunity for meeting the personal requirements in the field of orthoses – the most important link of the patient-doctor relationship aiming for improving the quality of life.

Acknowledgements

This work was supported in part by EU Horizon 2020 MSCA RISE project “Cyber-Physical Systems for PEdagogical Rehabilitation in Special Education (CybSPEED)“, JSPS KAKENHI (16H01616, 17H06383) and the New Energy and Industrial Technology Development Organization (NEDO), Project on Regional Revitalization Through Advanced Robotics (Kyushu Institute of Technology/Kitakyushu city, Japan) and Kitakyushu Foundation for the Advancement of Industry, Science and Technology (FAIS).

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