Increasing Hip Prostheses' Lifespan

19 AUG 2015 BY BRUNO JETTÉ, GUILLAUME FRÉCHETTE, OLIVIER GUILLEMETTE, ROBIN GAUDREAU, CHARLES SIMONEAU, PATRICK TERRIAULT AND VLADIMIR BRAILOVSKI

Abstract

This paper presents the design and manufacturing path leading to the creation of a biomimetic low-stiffness hip prosthesis. This path is based on the use of metallic porous structures and additive manufacturing technology. The retained concept has undergone numerical simulations and mechanical testing, and it stiffness comes close to that of bone.

Background

A hip prosthesis is mainly composed of a femoral stem and a spherical joint combined with an acetabular cup (see Figure 1). In general, the femoral stem is manufactured from biocompatible metals but metals are much stiffer than human bone, which leads to a non-uniform stress distribution in the instrumented femur known as "stress shielding". This phenomenon results invariably in bone resorption or bone loss in the femur tissue surrounding the implant. Over the long-term, the femur weakens, can develop cracks which would require prosthesis replacement surgery (Beaupré, Orr et Carter, 1990; Ridzwan et al., 2007). Such a replacement requires a lot of care and causes prolonged patient convalescence.

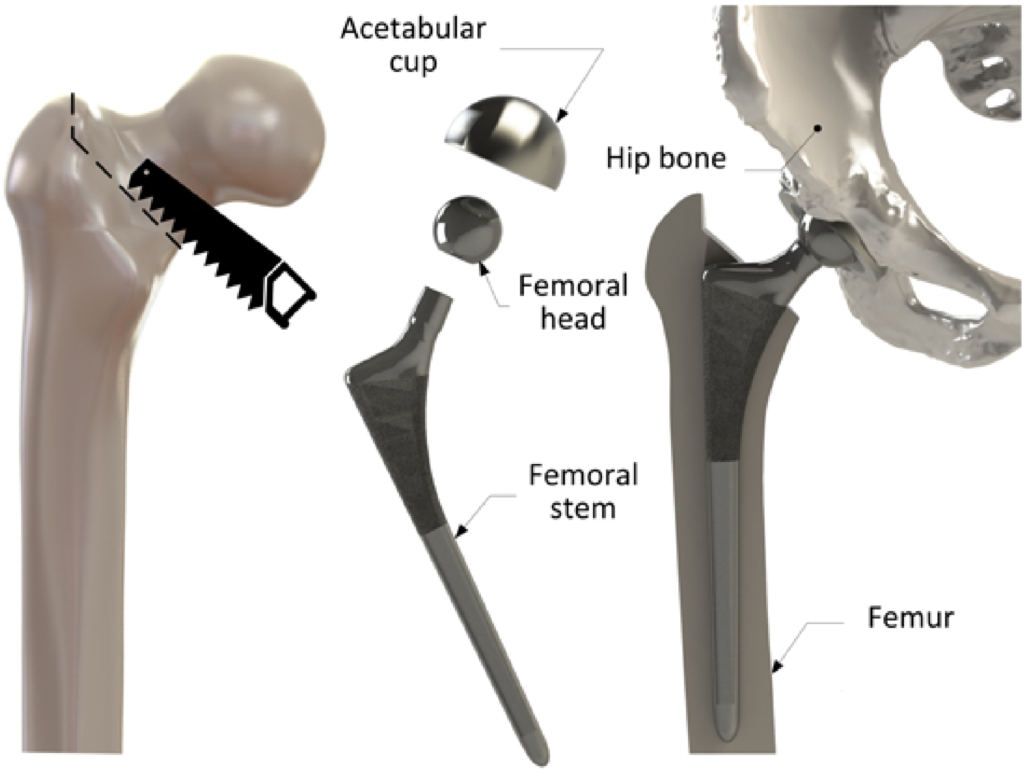


Figure 1 Insertion of a Complete Hip Prosthesis

According to the Canadian Joint Replacement Registry (CJRR) and the Canadian Institute for Health Information, the number of hip prosthesis replacements has more than quadrupled over the last 10 years (CIHI, 2004; 2014). Based on these numbers, l'Institut Calot (France) determined that the lifetime of a traditional, complete hip prosthesis varies between 15 and 25 years (Cazenave, 2011). In view of the aging population and the fact that more and more young people are receiving hip arthroplasty (surgical procedure involving the installation of a hip prosthesis), it is imperative to optimise the femoral stem mechanical characteristics to mimic as close as possible the intact femur (Gard, Iorio et Healy, 2000).

In the winter session of 2015, this engineering challenge was addressed by a Bachelor of Mechanical Engineering end-of-studies project at École de technologie supérieure de Montréal (ÉTS). The project team consisted of four final-year students, Bruno Jetté, Guillaume Fréchette, Robin Gaudreau and Olivier Guillemette, who were supervised by Patrick Terriault and Vladimir Brailovski, professors in ÉTS Mechanical Engineering Department as well as co-directors of the Shape Memory Alloys and Intelligent Systems Laboratory (LAMSI). In addition, M. Brailovski holds the ÉTS Research Chair on Engineering of Processes, Materials, and Structures for Additive Manufacturing (CIFA).

Design and Resolution

In concrete terms, the project objective aimed at designing a femoral stem exhibiting flexibility comparable to a healthy femur. The prosthesis design was based on an additive manufacturing process.

The strategy consisted in modeling a femur/femoral stem assembly that exhibits the same displacements as an intact femur when subjected to typical loads. The model would then be used to evaluate the femur/femoral stem assembly flexibility and compare it to that of a healthy bone. The concept was evaluated using a single type of load, the stair-descent. This ordinary, repetitive motion results in application of particularly-large forces on the hip (Bergmann et al., 2001; Morlock et al., 2001). The load was determined for a hypothetical 1.83 m (6 ft.) tall, 100 kg (220 pounds) patient and the 3D models for the femur and the femoral stem were determined accordingly (Heiner et Brown, 2001) (see Figure 2).

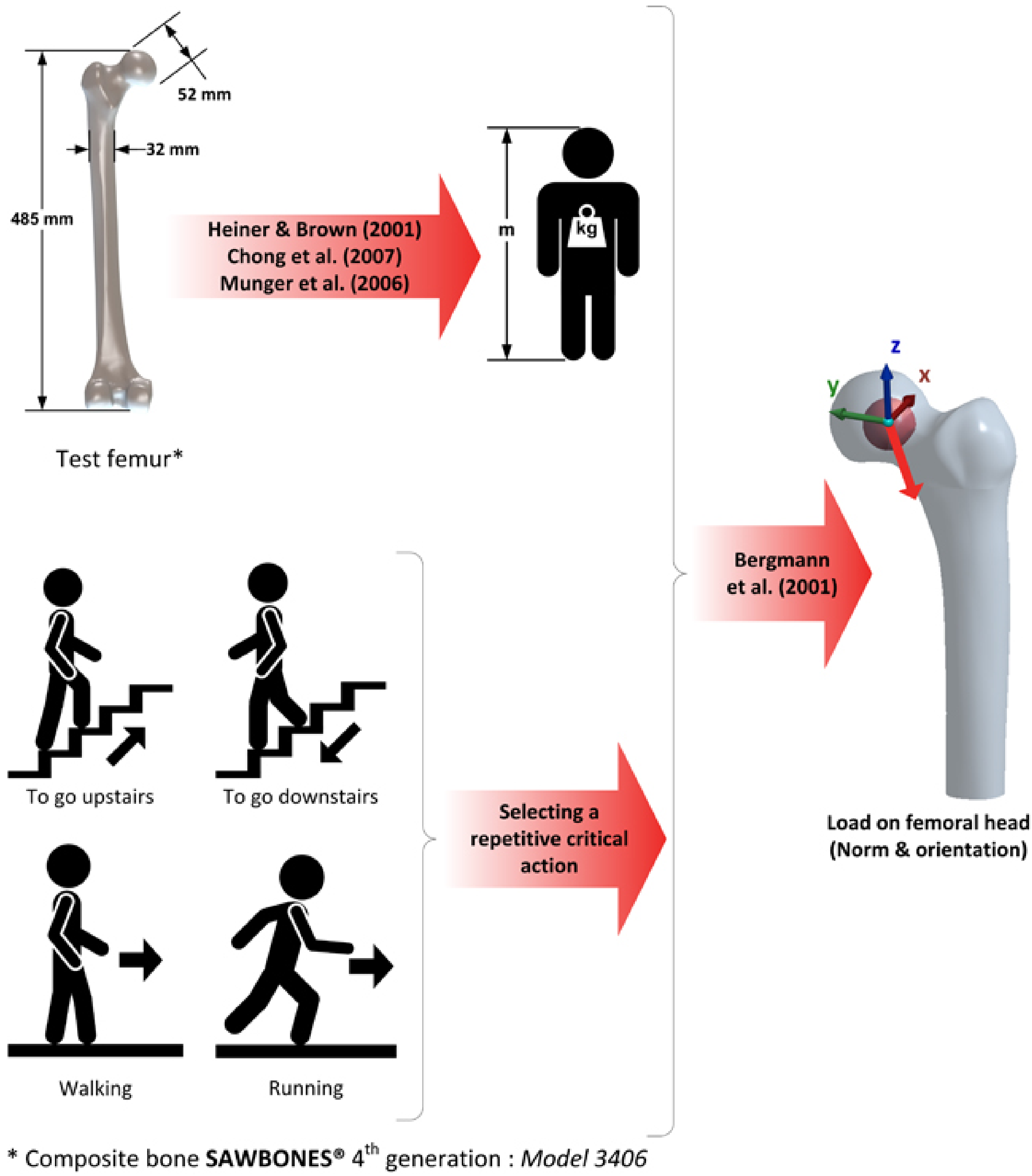


Figure 2 Method Used to Determine the Femoral Head Loads

Computer simulations were carried out using ANSYS Workbench 15 in order to evaluate and compare the various displacements as a function of load applied to the intact femur as well as to the femur/femoral stem assembly.

An open-porosity cellular structure was modelled for the central portion of the femoral stem (see Figure 3).

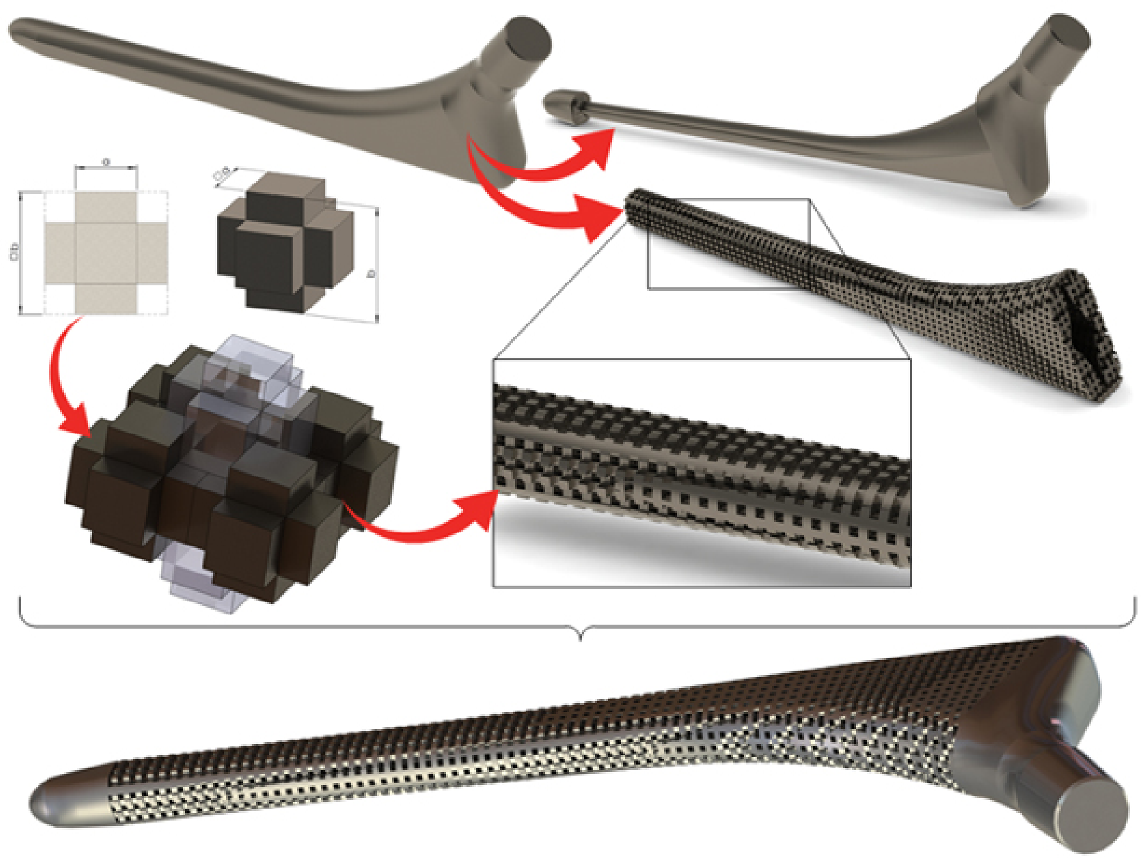


Figure 3 Modelling the Femoral Stem

This porous structure is intended to reduce the stiffness of the femoral stem and to confer to the femur/femoral stem assembly a mechanical behaviour similar to that of an intact femur. Moreover, such a porous structure is meant to provide an added benefit of facilitating bone ingrowth (osseointegration). Bony tissue could form inside the interstices of the porous structure of the femoral stem and provide better fixation of the stem inside the femur when compared to entirely dense stems. At the same time, this would also help to avoid the use of polymeric cement between the stem and the medullary cavity.

Prototype Fabrication

The femoral stem prototype was manufactured in the ÉTS Additive Manufacturing Lab with an EOSINT M280 machine using a Selective Laser Melting (SLM) power bed process. The feedstock powder is a biocompatible, EOS Cobalt-Chrome MP1 alloy.

Figure 4 Prototype Fabrication Processes for Mechanical Testing

Prototype Evaluation

Computer modeling and, mechanical testing were used to assess the stiffness of the manufactured stem prototype. For this purpose, the combined numerical-experimental approach was used to characterise the relationship between the overall deformation of the femoral stem and the application of an experimental load (see Figure 5).

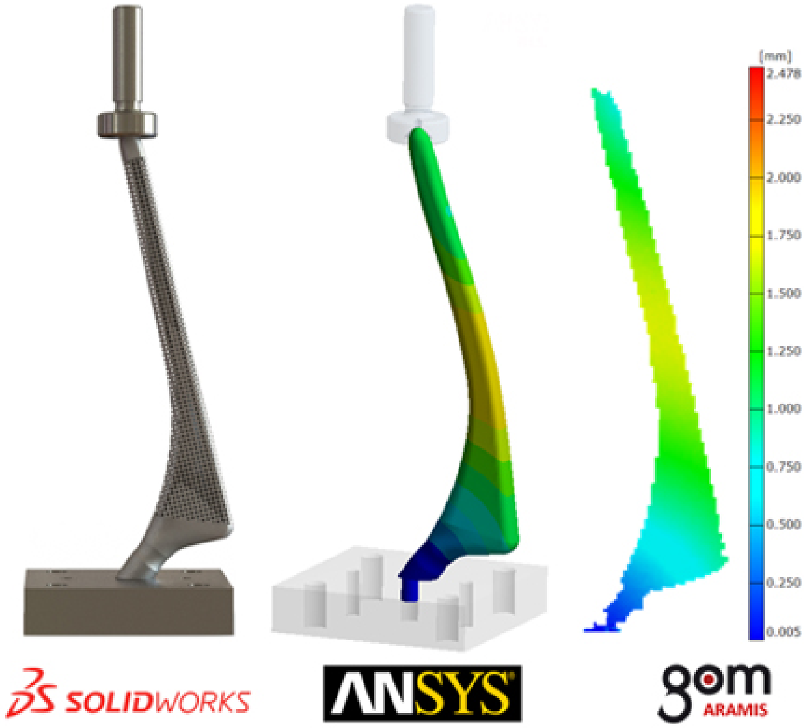


Figure 5 Mechanical Testing and Characterisation of the Stem Behaviour as a Function of Load. On the left: The bench-test, 3D model. In the centre: The finite-element model was adjusted to correlate the measurements made during mechanical testing using an ARAMIS optical data acquisition system (on the right).

The results of the mechanical tests and computer simulations have shown a significant improvement in the femoral stem flexibility facilitated by its porous structure. Technically, a 0.58 mm displacement at the load application point of 3097 newtons was considered as a target displacement, since it corresponded to that of the intact femur under the same load. In the study, the mechanical response obtained with the femoral stem containing the porous structure yielded a displacement of 0.56 mm, which is only 3% below the target. The computer model of a femoral stem without a porous structure, i.e. completely solid, resulted in a displacement of 0.43 mm, which is more than 25% below the target. A comparison of these load configurations is shown in the following figure.

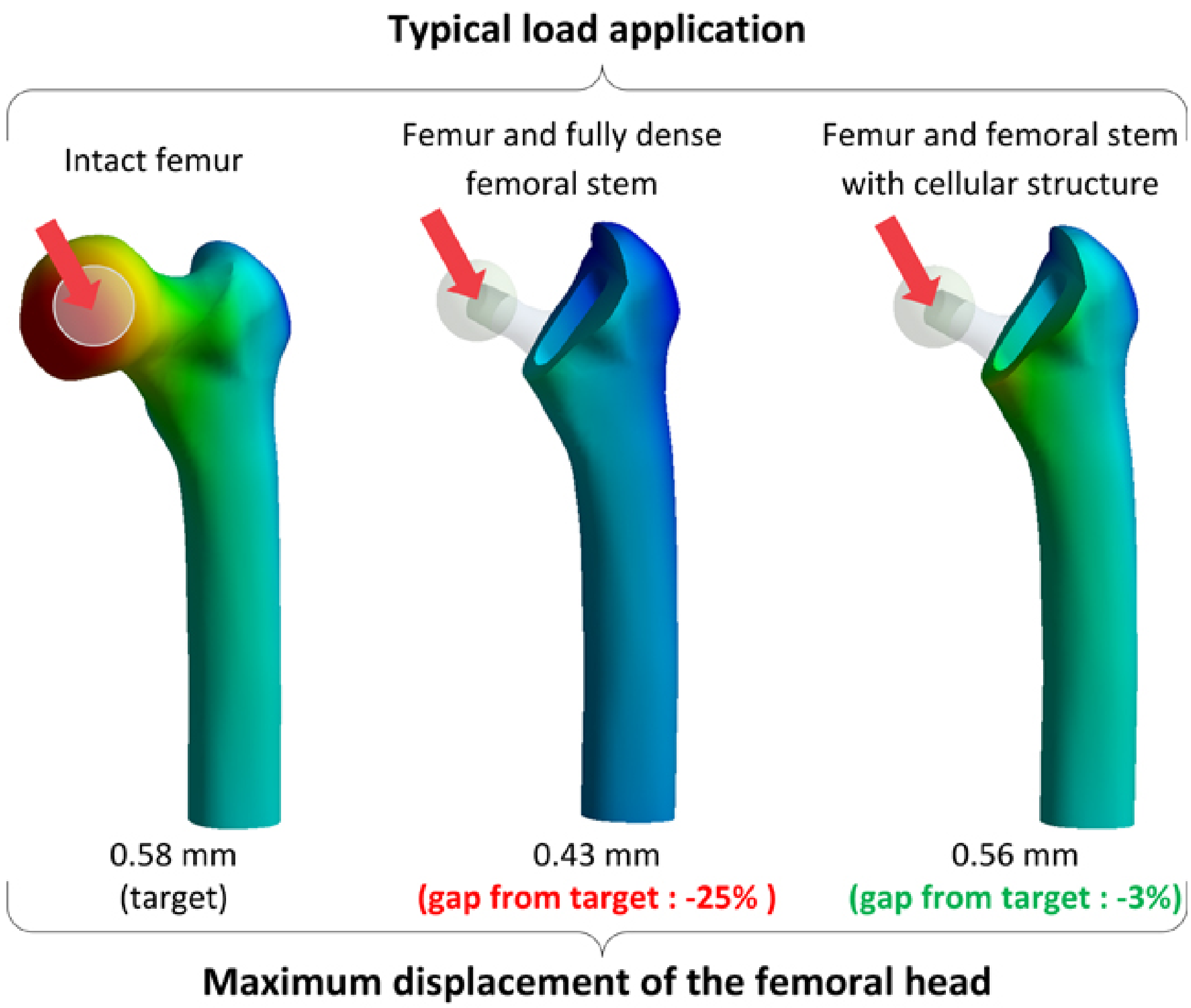


Figure 6 Displacement Comparison using Finite-Element Analysis and ANSYS Workbench 15

Observations and Conclusions

In summary, it has been shown that femoral stem prototypes made in this study highlighted the potential of additive manufacturing processes to create complex geometric shapes. Furthermore, by integrating such complex structures into a specific part, additive manufacturing has allowed the replication of a targeted mechanical behaviour.

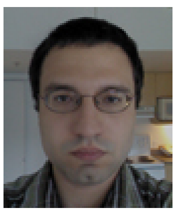
It should be noted that metallic materials that are less stiff than the Cobalt-Chrome alloy could be used to obtain even greater femoral stem flexibility. Finite-element simulations of the same porous structure as that used in this study, but manufactured with a titanium alloy and the same porous structure as that used in this study, validated this assumption.

The next step to improve the femoral stem design would be an optimisation of the dimensions, orientation and distribution of pores in the structure with an objective to create a more uniform load distribution between the femoral stem and the femur. An efficient, topology optimisation algorithm could help in pursuing such a refinement work (to be followed).

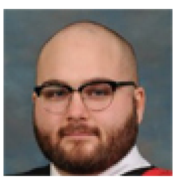
Authors

Bruno Jetté (team coordinator) is a Bachelor final-year student in Mechanical Engineering at ÉTS. He will soon begin a Master degree in LAMSI and his project will be on topology optimisation of components for additive manufacturing.

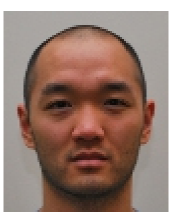
Guillaume Fréchette (team member) is a Bachelor final-year student in Mechanical Engineering at ÉTS. He will begin a Master degree in the winter session of 2016 with the Institut de recherche d'Hydro-Québec (IREQ).



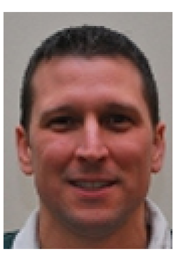
Olivier Guillemette (team member) is a Master student in the Thermo-fluid for Transport Laboratory (TFT) at ÉTS and his projects thesis are on computer modeling of fuel injection in a jet engine.



Robin Gaudreau (team member) has a Bachelor degree in Mechanical Engineering at ÉTS and work as a technical designer/draftsman in the industrial manufacturing field.



Charles Simoneau is a PhD student at LAMSI de l'ÉTS. His research thesis is on the Multi-scale modeling of materials made from powder sintering for medical applications. He offered technical support for the prototypes and the test coupons fabrication.



Patrick Terriault is a professor in the Mechanical Engineering department at ÉTS and is also director of LAMSI. He also supervised the students.

Professor Vladimir Brailovski is involved in several multidisciplinary projects requiring expertise in materials, design, and manufacturing processes. For the past 20 years, he has been deeply invested in the design and manufacture of devices in shape memory alloys and has achieved international recognition in this field. Additive manufacturing is a natural extension of his research activities in the field of shaping processes. He is a full professor at the mechanical engineering department of the École de technologie supérieure (ÉTS), in Montréal.

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IMAGE REFERENCES