



Stress-Shielding Effect (part 1)



Review

When the Total Hip Replacement Fails: A Review on the Stress-Shielding Effect

Davide Savio  and Andrea Bagno *

Department of Industrial Engineering, University of Padova, 35131 Padova, Italy;
davide.savio.3@studenti.unipd.it

* Correspondence: andrea.bagno@unipd.it

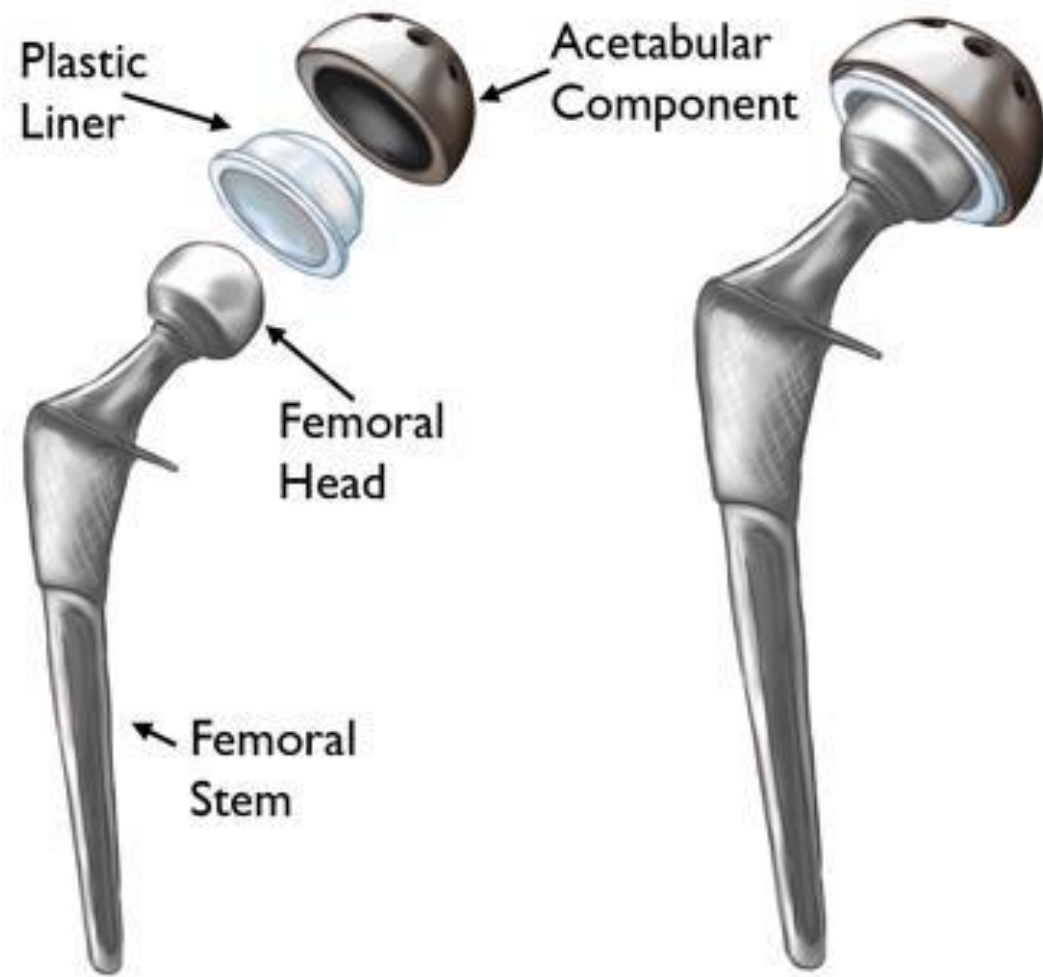
Total hip prosthesis

The main function of the hip joint is to provide dynamic support to the body weight, transmitting loads from the axial skeleton to the lower limbs.

The hip plays a primary role in locomotion but it is exposed to many risks and damages that can lead to pathological conditions.

The hip joint can be surgically replaced with a prosthetic device: the surgery may require the total joint replacement (total hip arthroplasty, THA), when both patient's femoral head and acetabulum are removed, or the hemi-replacement when only a part of the joint is replaced.

The hip resurfacing arthroplasty (HRA) is an alternative to the conventional THA: the femoral head is not removed, it is trimmed and capped with a smooth metallic surface.



The earliest replacements of the hip joint were performed in Germany: in 1891, Professor Glück exploited ivory as a biomaterial for substituting the femoral head in patients whose joint had been damaged by tuberculosis.

Since then, the development of novel design and the exploration of new materials has progressed continuously; the first total hip arthroplasty in the modern era was carried out in the early 1960s by Sir John Charnley, an orthopedic surgeon whose prosthesis model is still the most frequently used.



Sir John Charnley,
the father of the modern THA

Presently, hip replacement is one of the most common orthopedic operations and almost one million joint replacements are performed every year in the world.

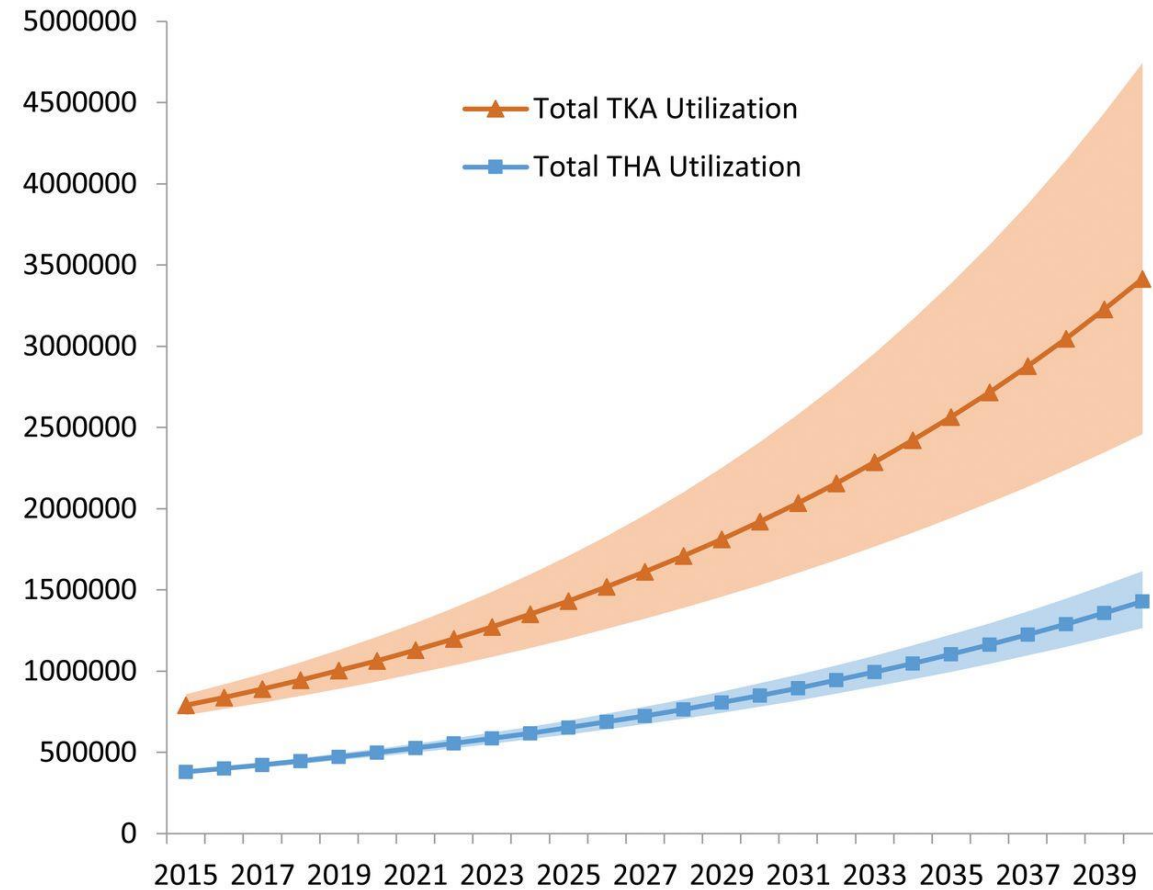
These numbers are inevitably going to grow with the increasing aging of the world population.

Since 2000, the number of hip and knee replacements has increased rapidly in most OECD (Organization for Economic Co-operation and Development) countries.

On average, hip replacement rates increased by 30% between 2007 and 2017 as a consequence of the rising incidence and prevalence of osteoarthritis, caused by aging and obesity.

In the United States, the total annual counts of THA is expected to increase by 75% in 2025 to 652,000 replacements; by 129% in 2030 to 850,000 replacements, and by 284% in 2040 to 1,429,000 replacements.

Trends are similar for both total hip and total knee arthroplasty: replacements are slightly more frequent in women and in individuals aged between 45 to 64 and from 65 to 84 years.



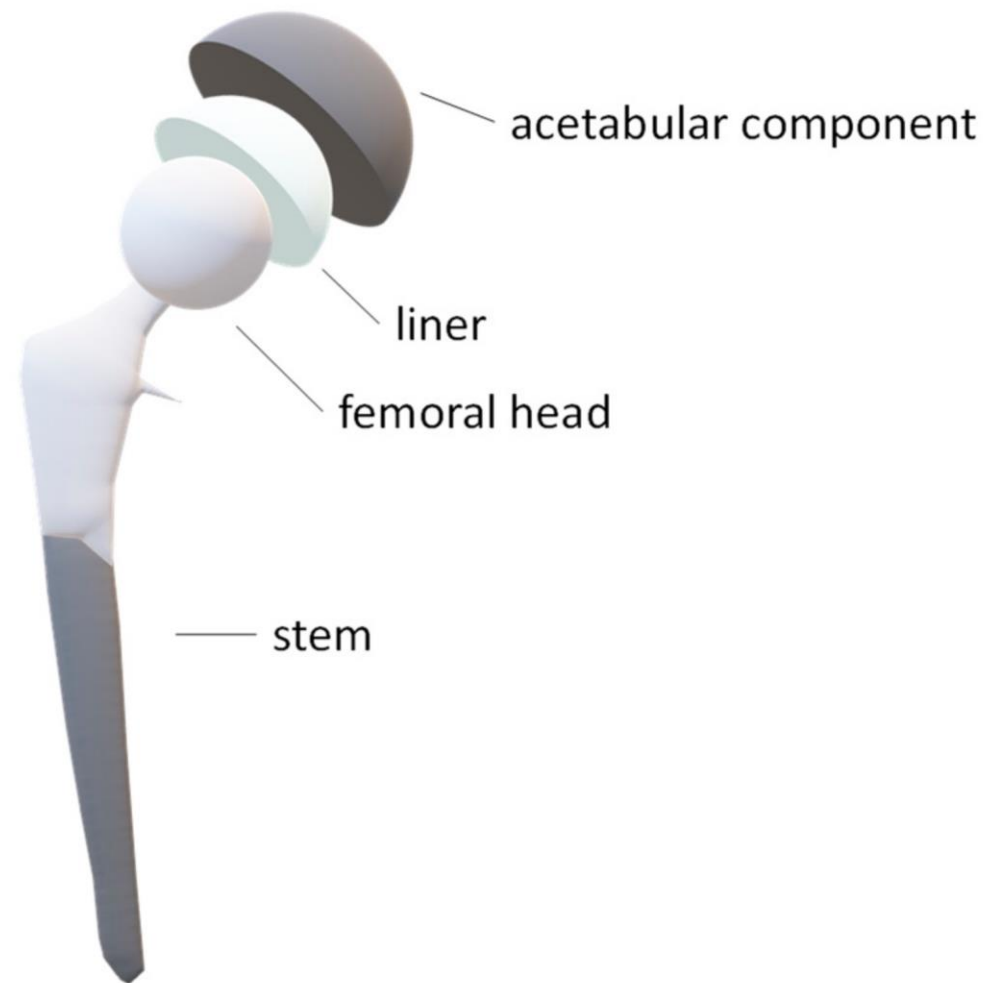
The projected annual use of primary total hip arthroplasty (THA) and primary total knee arthroplasty (TKA) procedures in the United States from 2015 to 2040

THA is indicated in patients suffering from severe osteoarthritis, juvenile rheumatoid arthritis, and in people with compound fractures of the femoral head or bone cancer.

The main objective of THA is the complete restoration of the original biomechanical balance of the coxofemoral joint.

Hip replacement has to function under high mechanical loads for many years and the mechanical strength of the materials used, combined with their biocompatibility, is crucial.

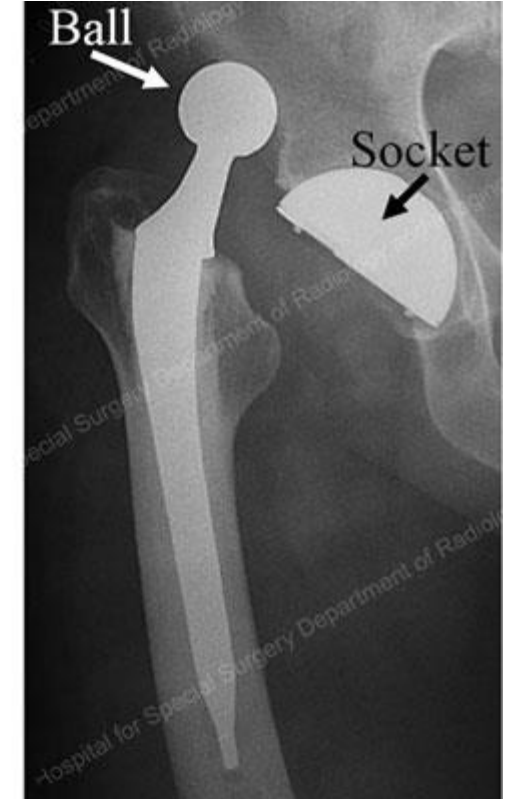
Typical components of a total hip prosthesis are the cup (also called acetabular component, made of metallic or polymeric materials), the ceramic or polymeric liner, the femoral head (made of metals or ceramic materials), and the metallic femoral stem.



Various are the possible causes of hip prostheses failure, including bone fracture, dislocation, deep vein thrombosis, pulmonary embolism, abductor muscle failure, wound complications, infection (septic mobilization), rupture of prosthetic components, wear and aseptic mobilization: the latter can be due to the stress-shielding phenomenon.

Generally speaking, periprosthetic bone loss caused by the stress shielding effect depends on both implant characteristics (design, materials, etc.) and bone quality.

Mechanical based models are useful for predicting bone adaptation and rely on mechanical stimuli such as stress, strain, and strain energy.



Why Does the Stress-Shielding Appear?

Generally, the stress applied to the bone promotes its physiological remodeling in healthy individuals.

This evidence had been expressed by **Julius Wolff** in the 19th century: his law describes the capacity of healthy bone to adapt to variable loading conditions: *“bone in a healthy animal will adapt to the loads under which it is placed”*.

The term “**mechanosensation**” has been recently introduced to indicate the ability of bone tissue to dynamically modify its morphology: new bone is added to withstand increased loads, whereas bone is resorbed when unloaded or disused.

The exact mechanism of bone adaptation to load has not been completely understood, but it is acknowledged that **a number of stimuli can be detected by the osteocytes, which can sense the mechanical load and transduce it into a specific biological activity.**

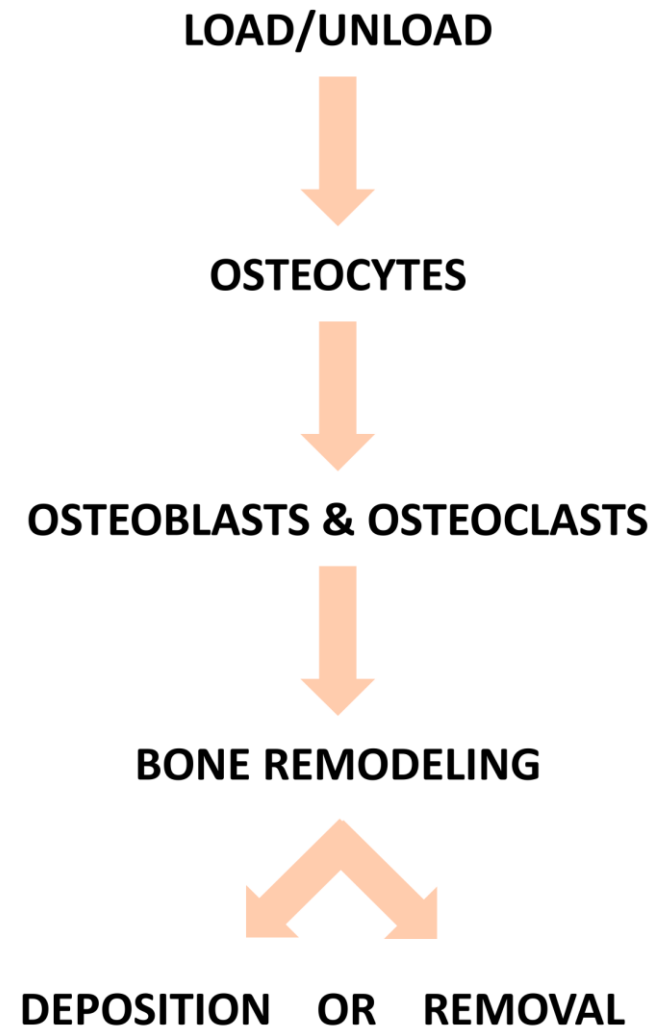
Osteocytes are terminally differentiated osteoblasts that reside within the bone matrix; they are sheltered into lacunae but still able to communicate with each other.

Osteocytes play a fundamental role in **mechanosensation** (or **mechanotransduction**) thanks to their capacity to coordinate the regulation of bone mass and structure: indeed, they release biochemical factors that control the activity of both osteoclasts and osteoblasts.

Osteoclasts are large, multinucleated giant cells formed from the fusion of mononuclear progenitors and are mainly responsible for bone resorption; osteoblasts derive from mesenchymal stem cells in the bone marrow and are responsible for bone matrix deposition and mineralization.

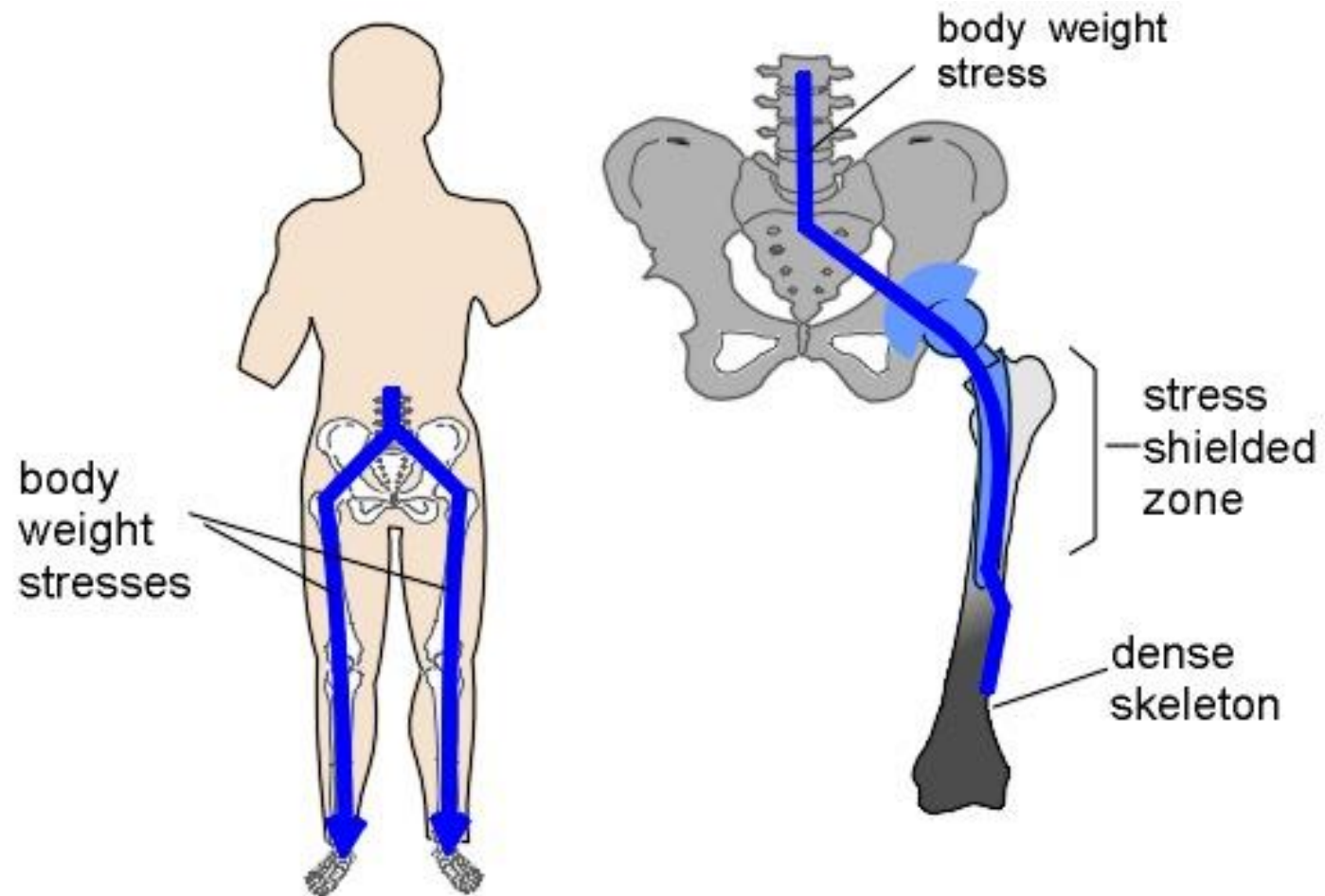
Physiologically, **bone remodeling is necessary to repair damaged bone and avoid the effects of aging.**

Thus, the maintenance of healthy bone is eventually assured by the balanced actions of osteoclasts (resorption) and osteoblasts (deposition), whose orchestrated functions result in the correct bone remodeling



When the body weight is equally distributed over the lower limbs, the remodeling is properly regulated.

Viceversa, when a prosthetic device is introduced into the bone, it significantly modifies the distribution of loads, thus altering the appropriate bone remodeling: in particular, the presence of the hip prosthesis can induce the formation of atrophic bone in the region of the femur that is no longer physiologically loaded (stress protected or stress shielded zone) and denser bone in the area exposed to stresses higher than physiological.



The phenomenon is a direct consequence of the different mechanical properties (stiffness) between the bone tissue and the implanted materials: for example, metals have significantly higher stiffness values than both cortical and spongy bone.

Material/tissue	Elastic Modulus E [GPa]
Cortical Bone	16
Spongy Bone	0.1
316L Stainless Steel	200
Ti6Al4V Alloy	110
CoCr Alloy	230

This gap causes the stress-shielding effect, exposing the atrophic bone, of poor quality, to possible fractures.

This event can be intuitively explained by considering the stem and the femur as an extremely simplified mechanical model composed of two springs in parallel: the one with a higher elastic constant (the metallic stem) will be loaded with a greater amount of external force.

In this sense, the magnitude of femoral stress shielding can be estimated using the “composite beam theory”.



This analytical method predicts that the reduction in femoral stress following the implantation of a prosthesis is proportional to the relative structural stiffnesses of bone and femoral stem.

Therefore, a stem with a large diameter will cause a more significant bone loss compared to a device with a smaller diameter implanted in the same anatomical site.

The study by Engh and Bobyn reported that the incidence of osteolysis following arthroplasty with an uncemented stem increases contextually with the increase in the degree of stress shielding predicted by the compound beam theory.

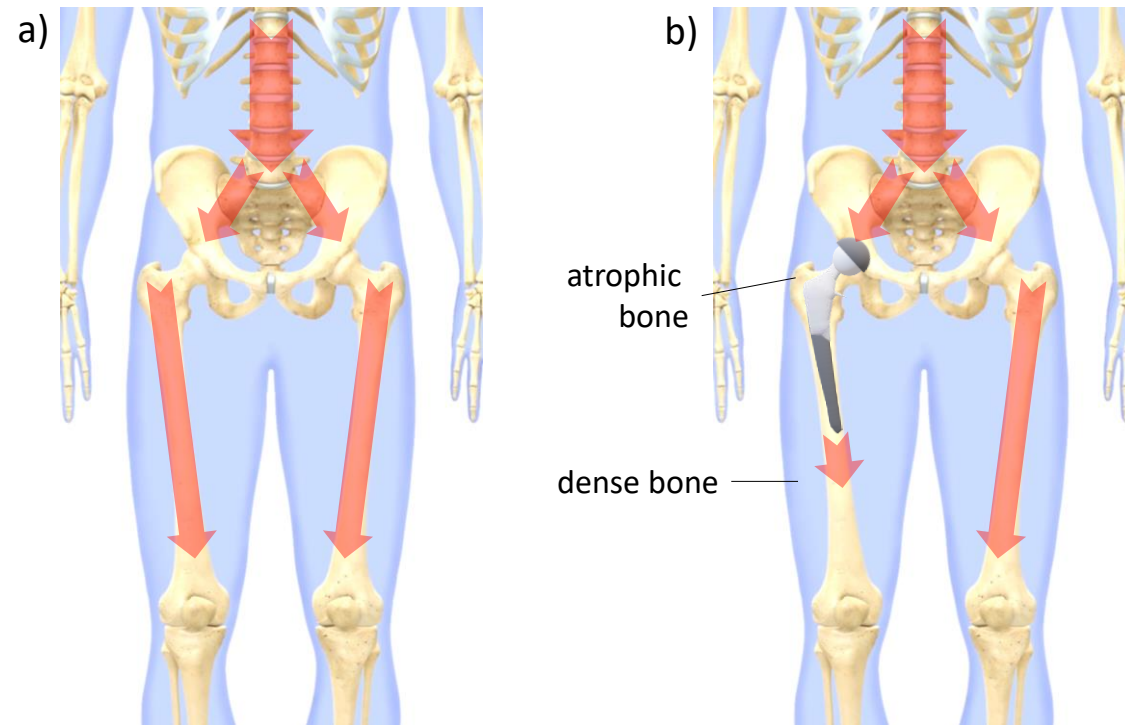
Osteolysis is also related to possible aseptic loosening of the implant.

Mechanical loosening due to the physiological response of the bone, which is dynamic, is one of the main factors negatively affecting an implant's lifespan.

In this sense, it has been recognized that the choice of material with superior mechanical characteristics is not always the best solution.

When the prosthesis is inserted into the medullary canal of the femur, the load that is normally applied to the proximal portion of the femur is drastically altered, causing bone resorption, bone loss, thinning of the cortical bone, and, in some cases, failure of the prosthesis.

By inserting the femoral component of a total hip prosthesis, the stresses on the proximal and medial regions of the femur are reduced, because most of the load bypasses this area and is transmitted from the metal shaft to the distal portion of the femur.



Stress-Shielding Effect (part 2)

How to prevent the femoral stress-shielding?

In order to guarantee the correct distribution of stresses and prevent bone resorption resulting from the stress-shielding effect, several solutions have been developed over the years with specific regard to the femoral component of the hip prosthesis.

- *Prosthesis (re)design*

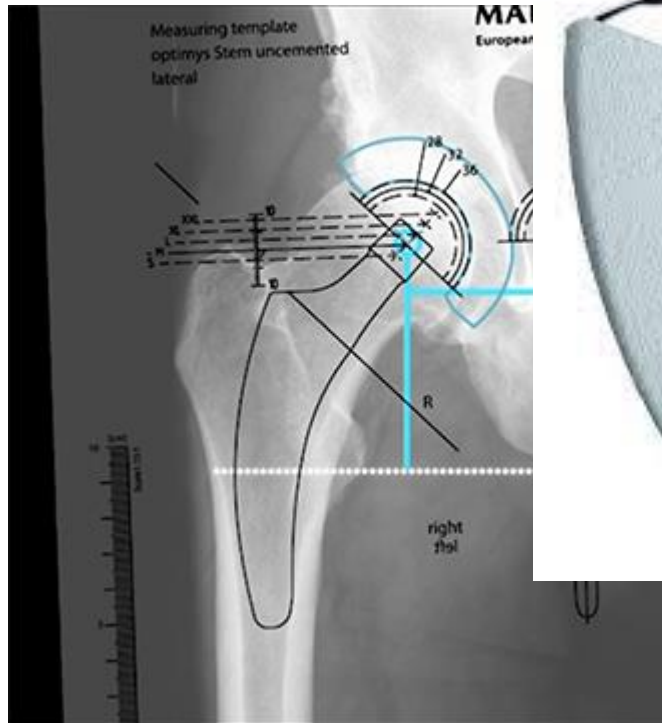
Being the stress-shielding phenomenon due to the altered distribution of load because of the presence of the prosthetic system, several efforts have been addressed to redesign the prosthetic device in order to transfer the load to the bone in a more physiological way.

- *The short stem*

Hip prostheses with **short stems** have been developed: the femoral component generally measures less than 120 mm in length (distance from the center of the head to the apex of the stem), allows conservative surgery, and assures a better transmission of the load.

However, long-term clinical outcomes are still lacking: thus, the performance of the prosthesis has been evaluated in vitro.

The study published by Bieger et al. analyzed the primary stability and the stress-shielding effect associated with a short stem prosthesis (optimys TM, Mathys, Bettlach, Switzerland) and a conventional device (CBC TM, Mathys) in nine pairs of human cadaveric femurs.



short stem



long stem



The results suggest a more uniform load distribution in the proximal medial portion for the short stem prosthesis, with a stress variation of approximately 47%.

On the other hand, the conventional design reveals an altered load of about 80%.

In the proximal lateral section, the change is limited (about 6-7%); in the central portion, differences are moderate, especially in the lateral part; in the distal region, differences are significant: **the short stem guarantees a more uniform distribution of the load** with percent differences ranging from approximately 12% for the lateral portion to 7-8% for the medial section.

With regard to the **micromotions**, the authors stated that the short stem displayed lower values at the proximal compared to the distal points, with the opposite findings around the straight stem: this finding suggests a more stable metaphyseal fixation of the short stem and a more diaphyseal anchorage of the straight one.

These results have been confirmed by numerical studies, which found a smaller stress-shielding effect in the proximal femur following implantation of short stems compared to longer stems.

- *The hollow stem*

The stiffness of the stem depends on the geometry of its cross-section and on the elastic modulus of the material: it has a crucial influence on the stresses absorbed by the entire prosthetic system and, consequently, on the stress-shielding effect.

The results obtained by Gross and Abel showed a reduced proximal stress-shielding effect using stems with hollow sections.

Different designs have been compared and some of them provided superior performances at least by finite element analysis.

Indeed, the advantage of the hollow configuration lies on the possibility to control stem stiffness through the overall design and the choice of internal diameters.

The authors showed that increasing the internal diameter simultaneously increases the load applied to the bone, both for an external diameter of 10 mm and for one of 11 mm: in the first case, the load progressively increases up to an equivalent von Mises tension of 7.28 MPa, increasing the proximal stress value by 18.37% compared to the solid stem.

The result is even better in the case of an external diameter of 11 mm, with an increase in proximal stress of 28.21% in the case of a stem with an internal diameter of 9 mm.

They also suggested that the external shape of the stem can be defined on the basis of single patient's anatomical requirements.

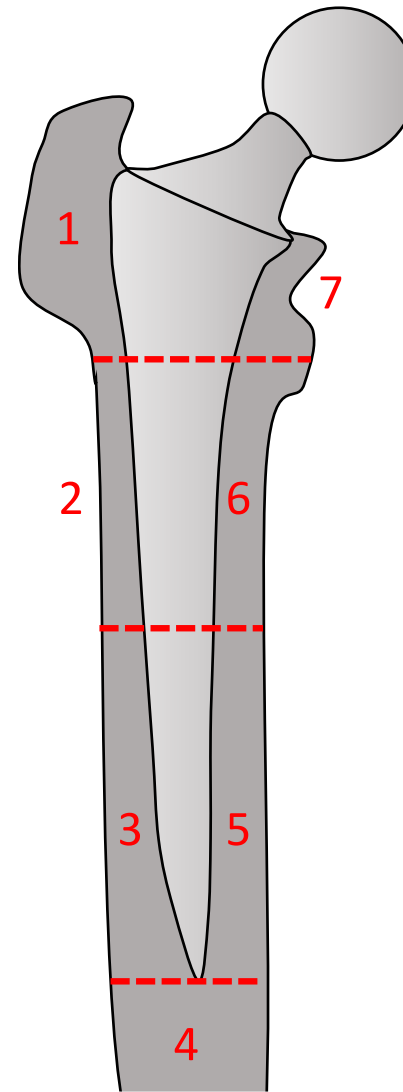
- *The Ribbed stem*

The study by Wu et al. evaluated the effects of the ribbed anatomic cementless femoral stem on bone remodeling and bone mineral density (BMD) in 41 patients (19 males and 22 females, average age 62.07 years).

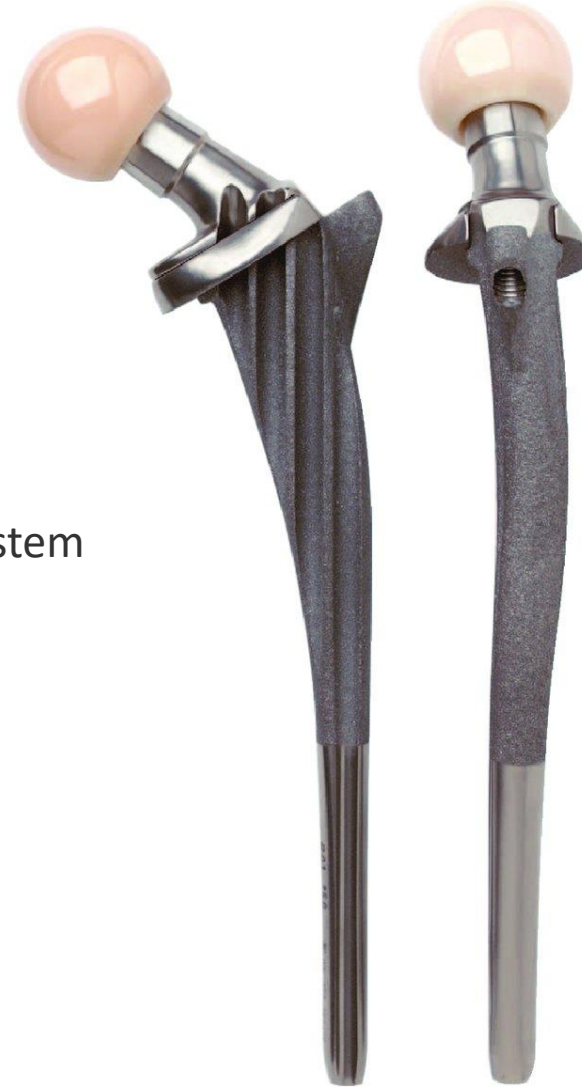
The short and medium-term follow-up of patients who received the grooved stem prosthesis (Ribbed Hip system), pointed out a restrained osteolysis in the proximal areas of the femur.

BMD of the seven Gruen zones was measured by dual-energy X-ray absorptiometry, and contact, fitness, and fixation of the femoral stem and proximal femur were analyzed by X-ray.

The Gruen zones (marked from 1 to 7) are conventionally used to identify the areas of the prosthetic system where bone remodeling has to be assessed



Ribbed cementless anatomic femoral stem



Compared with the contralateral unoperated side, significant reductions of periprosthetic BMD were detected in the Gruen zones 4 and 5 on the prosthetic side.

Other significant differences were not detected.

Authors concluded that BMD changes imply that more proximal stress is distributed in proximal lateral region (Gruen zone 1: + 5.542%) and middle medial zone (Gruen zone 6: + 1.617%), accompanied with evident stress-shielding in distal zone (Gruen zone 4: - 5.799%) and medial distal zone (Gruen zone 5: - 2.845%).

- Surface Treatment and Coating

Several attempts to promote the fixation of the stem to the femur have been investigated and implemented, with specific regard to the treatment of the **prosthetic surface**.

Two kinds of cementless prostheses have been developed: those promoting bone growth on the surface of the prosthetic stem itself (**ongrowth**) and those promoting bone growth within a microscopic three-dimensional structure that coats the body of the prosthesis (**ingrowth**).

- Ongrowth Anchoring

To promote the anchorage of the prosthetic stem to the bone by ongrowth, surface modifications are applied: they allow retaining the desired bulk properties of the stem while modifying the external surface, which is directly in contact with the biological tissue.

Surface modifications can be achieved by several approaches.

In particular, two techniques are usually employed: **sandblasting** and **plasma spray**.

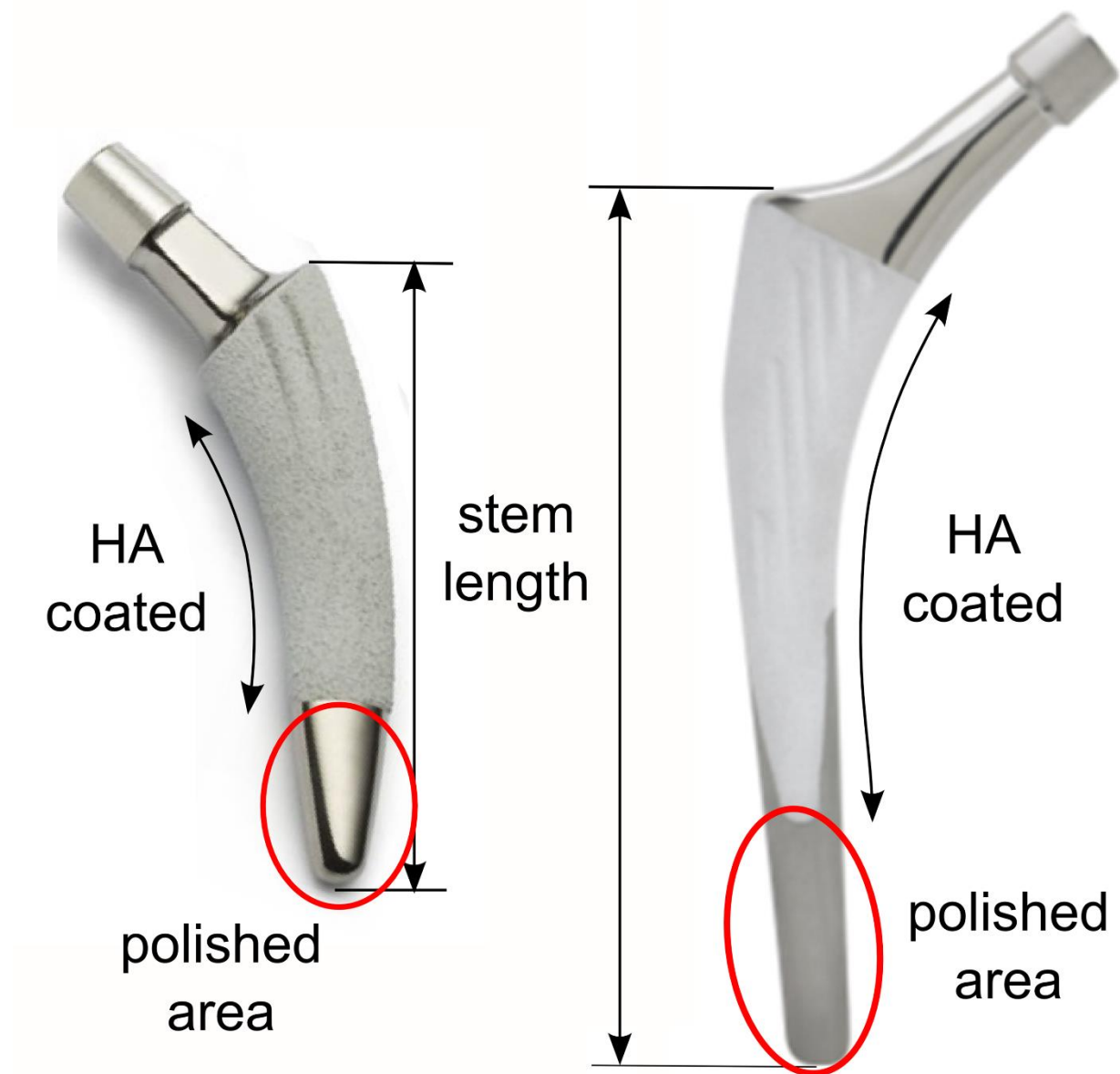
Sandblasting requires **abrasive particles** (e.g., **alumina**, **corundum**, **rutile**) to be dragged into a pressurized fluid against the surface: the impact of the particles increases surface roughness, which value mainly depends on particles size and treatment duration.

Hydroxyapatite (HA) coating is a particular type of plasma spray technique: HA is a phosphocalcic ceramic and represents the main mineral component of the bone tissue matrix.

HA coatings are acknowledged to offer some advantages: they stimulate bone formation, accelerate implant fixation to bone, reduce the risk of release of metallic wear particles or metallic ions from implants.

Once a strong osteo-apposition is achieved, HA gradually disappears due to bone remodeling: therefore, the HA coating is replaced by newly grown bone.

HA has been widely applied to coat metallic stems and it is recently proposed also to coat composite stems (see CF/PA composite).



Clinical studies have shown that fully HA-coated stems are associated with greater stress-shielding than those coated only in the proximal region.

Currently, the amount of coating on most prosthetic stems is still inadequate to reduce the proximal stress-shielding effect.

However, the reduction of the porous coating has to be balanced with the amount of coating necessary to ensure a solid implant fixation

- Ingrowth Anchoring

The fixation of the prosthesis by bone ingrowth is based on the ability of bone cells to populate the pores present on the stem surface.

Scientific evidence have shown that an optimal bone ingrowth requires a pore diameter ranging between 100 and 400 μm .

Various technical solutions have been adopted to create these kinds of pores, including sintered metal microspheres over the prosthetic stems, micro-meshes made of metal fiber, and **porous metals**.

Moreover, a porous structure allows reducing the stiffness of the implant, an effective way to relieve femoral stress-shielding.

Porous metal implants ensure a more uniform stress distribution than smoothed ones and allow greater long-term stability.

However, it is worthy to consider that **an excessive reduction of stiffness can cause relative micro-movements between the implant and the patient's bone**; excessive micro-movements can hamper the formation of newly grown bone tissue, preventing the adhesion of bone cells to the implant surface.



Wang et al. demonstrated that the lower stiffness of porous femoral stems increases load transfer to the proximal femur compared to fully dense femoral stems: the introduction of porosity into the femoral stem design can alleviate the problem of stress-shielding around the prosthesis.

In particular, in the case of fully dense stems, the total volume of bone with decreased density is almost 75% higher than that of porous stems: this outcome explains the advantages of low-stiffness implants compared to high stiffness ones.

However, compared to dense titanium, **porous titanium has a lower fatigue resistance with a higher risk of fracture or long-term failure.**

Therefore, the problem of femoral stem fatigue should not be ignored, especially for porous stems.

- Innovative Biomaterials

Manufacturers of prosthetic devices have been progressively moving towards the **exploitation of biomaterials with mechanical features replicating those of the bone tissue rather than superior.**

The mechanical resistance of the stem depends on its thickness and on its elastic modulus (stiffness).

A clear relation between the mechanical characteristics of the prosthetic stem and peri-implant bone resorption had been illustrated by Huiskes, Weinans, and Van Rietbergen: working on embalmed femurs, these authors simulated and compared the effects caused by the presence of titanium stems ($E = 1.1 \times 10^5$ MPa) and stems made of flexible, isoelastic materials ($E = 0.2 \times 10^5$ MPa, $E = 0.5 \times 10^5$ MPa, $E = 0.8 \times 10^5$ MPa).

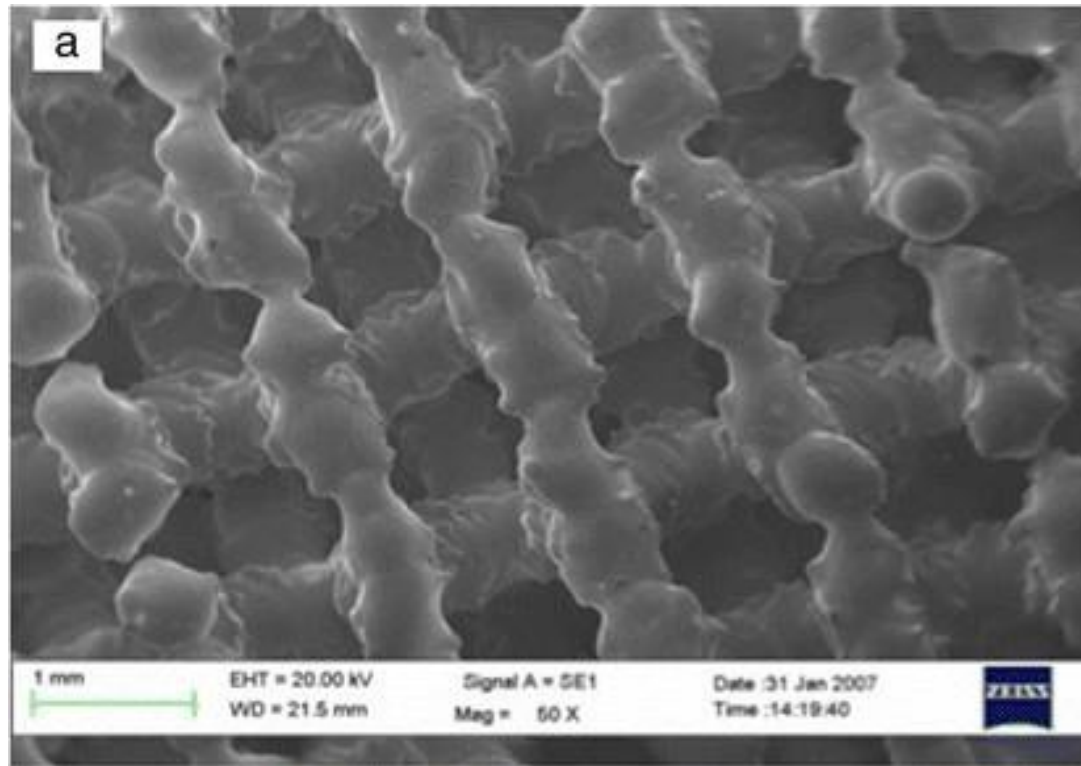
A 10% increase in stem thickness produces a 33% increase in stem flexural strength.

By reducing the longitudinal elastic modulus by a factor of 5.5 (using an elastic material with Young's modulus similar to that of cortical bone), long-term bone loss is considerably reduced, from 23% to 9%.

- Porous Titanium

In the paper by Arabnejad et al., a high-strength femoral stem was entirely made of **porous titanium**, whose mechanical properties were adjusted by varying the porosity.

The macroscopic design of the implant was based on the short stem concept, which is compatible with minimally invasive surgery; the microarchitecture of the implant was optimized by means of computational methods in order to locally emulate the properties of the bone tissue and minimize the stress-shielding effect.



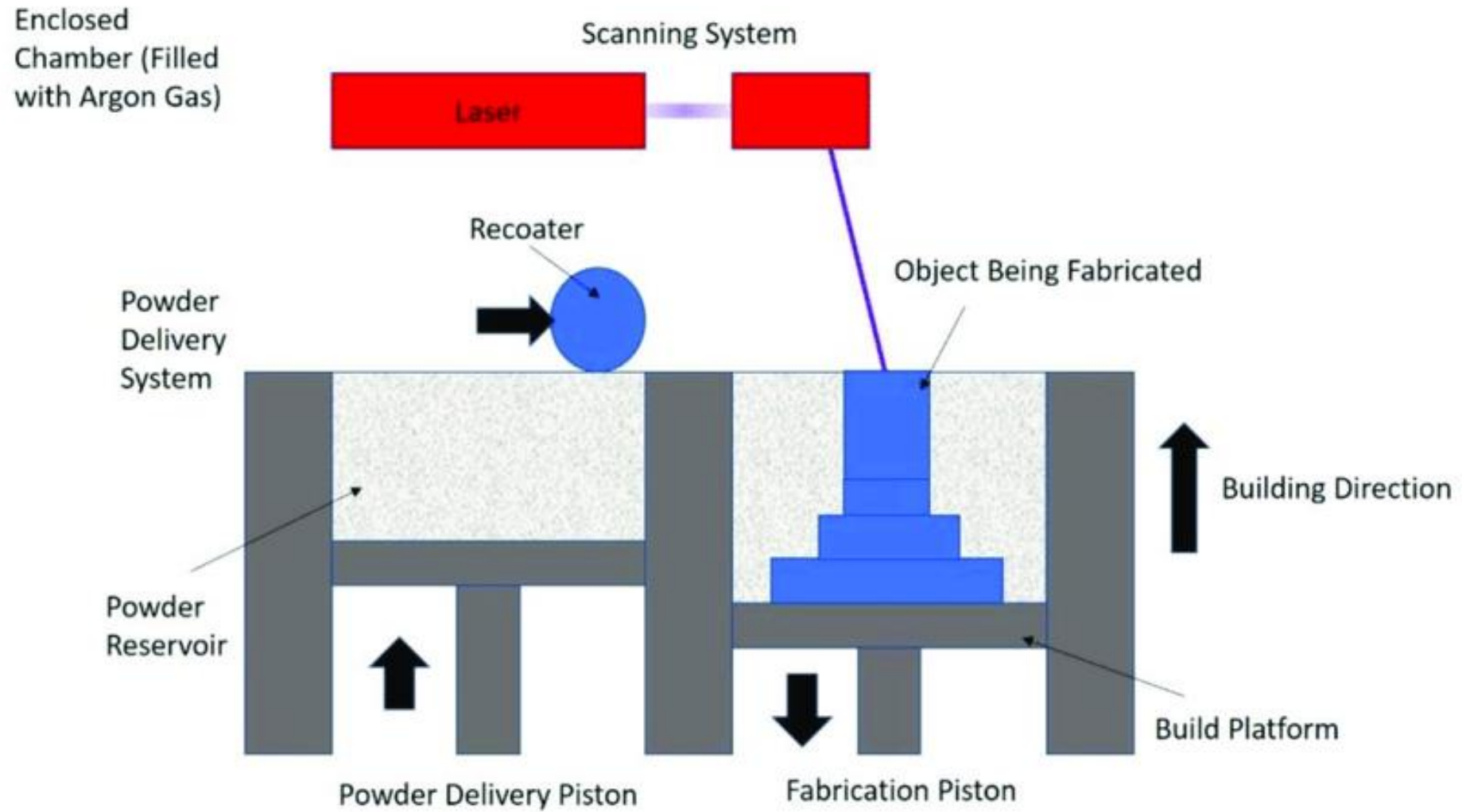
a) SEM image of the Trabecular Titanium cellular solid structure; b) Cementless acetabular cup in Trabecular Titanium™ (DELTA-TT, Lima Corporate)

Bone was considered isotropic material: indeed, this simplification did not involve significant differences with respect to the results obtained by considering bone as an orthotropic material.

Once the optimal density distribution was obtained, the stem was produced by **selective laser melting (SLM)**, an additive manufacturing technique using high power-density laser to melt and fuse metallic powders.

Porosity and pore size was set at 70% and 500 μm , respectively.

Bone resorption was assessed by the Digital Image Correlation (DIC) test comparing the porous stem with a commercially available implant of identical but solid geometry.



The physiological FEA model shows that the total bone loss due to the stress-shielding effect for the traditional stem was 34%, concentrated in the proximal medial portion (Gruen zone 7).

For the porous implant, the bone loss was only localized in the proximal medial portion (8%).

This outcome suggests that **osteolysis in a completely porous implant is 75% lower than in a traditional one.**

Furthermore, the bone loss was confined to a single Gruen region.

Moreover, with regard to the Gruen zone 6, the volumetric bone loss was reduced by 86% as shown in the FEA corresponding to the quasi-physiological DIC experiment.

In general, for the porous implant, the stress-shielding effects were considerably limited compared to a traditional implant.

- β Ti–33.6Nb–4Sn Alloy

Many attempts have been exploited in order to improve the mechanical features of the materials used for manufacturing the hip prosthesis components.

For example, elements such as iron and niobium have been added to titanium-aluminum alloys to get higher dynamic stiffness and lower elastic modulus.

Therefore, Ti₅Al_{2.5}Fe and Ti₆Al₇Nb alloys allow a better distribution of stress between the implant and bone tissue and a lower elastic modulus.

Another class of titanium alloys (β -Ti alloys) exploited for orthopedic applications contains molybdenum: its presence stabilizes the titanium phase at room temperature.

In 2014, Hanada et al. were the first to develop a new cementless stem with Young's modulus decreasing from the proximal to the distal area using the new β -Ti-33.6Nb4Sn alloy (TNS).

The longitudinal elastic modulus and the strength of this alloy depend on the temperature at which the heat treatment is carried out.

A local heat treatment (693 K for 5 h in N₂ atmosphere) applied in the proximal region, increases the resistance of the prosthetic neck compared to the Ti6Al4V alloy.

TNS stems were evaluated in a multicenter, open-label, single-arm clinical trial published by Chiba et al.

The results of 3-years follow-up on 40 patients were assessed and **revealed no radiologic signs of loosening, subsidence, or breakage of the stem.**

Indeed, this study presents some limitations (no control group, few patients, short follow-up): nevertheless, it confirmed that TNS alloy is suitable for the production of the stem component of a total hip prosthesis with a mild stress-shielding effect on 65% of patients.

The work of Yamako et al. demonstrated that a TNS stem causes bone resorption lower than a Ti6Al4V one in almost all the Gruen areas.

Bone loss occurred mainly in the proximal part of the femur (Gruen zones 1, 6, and 7).

The difference in BMD between the two stems gradually increased over time in the proximal regions.

- *CF/PEEK Composites*

It has been shown that **the properties of carbon fiber reinforced polyetheretherketone—PEEK (Carbon/PEEK or Carbon Fiber PEEK or CF/PEEK) are very close to those of human bones** and significantly different from those of other materials used for the manufacture of the hip prosthesis.

CF/PEEK composites can ensure a more uniform transfer of loads from implant to bone, thus limiting the stress-shielding effect.

The mechanical properties of these materials vary accordingly with the orientation of the carbon fibers and their overall fraction in the composite (strength ranging from 70 to 1900 MPa and stiffness between 10 and 100 GPa).

In addition, **the CF/PEEK composites have shown excellent biocompatibility, environmental stability, and chemical resistance.**

It is worthy to add that these materials can be produced with different arrangements of carbon fibers within the PEEK matrix: this can be the way to adjust the elastic modulus along the stem to reduce the stress-shielding effect.

In the study by Carpenter et al., a porous PEEK implant was compared with a porous titanium one.

The results confirmed that the former significantly increased the transfer of load to the bone compared to porous Ti under compression (PEEK = 66%; Ti = 13%), traction (PEEK = 71%; Ti = 12%) and shear (PEEK = 68%; Ti = 9%) evaluated over a 4-week period.

The extent of the stresses transmitted to the bone increased, on average, by 83%.

The application of the mechanical properties of PEEK to the geometry of the Ti implant, and viceversa, demonstrated that the increase in load sharing with bone was mainly due to differences in the intrinsic elastic modulus of the materials rather than to the architecture of the pores.

The study by Anguiano-Sanchez et al. demonstrated that a PEEK coating applied to a hip prosthesis improves the distribution of stresses in the proximal area, decreasing the stress-shielding phenomenon and increasing the lifespan of the implant.

The PEEK coating proposed in the study shows a 47% increase in load transfer in the proximal area with a 100 μm thick coating; increasing the thickness up to 400 μm , the stress transmission improves by 60%.

Another recent paper investigated the application of PEEK and CF/PEEK composite (with different fibers orientations) as coating materials: the analysis was carried out by the finite element method and demonstrated that both safety and durability of the prosthetic system are enhanced by CF/PEEK coating (with multidirectional orientation).

This coating material is able to distribute the applied load to the bone minimizing the stress-shielding effect.

Nakahara et al. investigated the radiographic and histological results for cementless or cemented CF/PEEK hip prostheses implantation in an ovine model.

After 52 weeks, five cementless and four cemented cases showed 1st-degree stress-shielding and two cemented cases showed 2nd-degree stress-shielding; 3rd-degree stress-shielding was not observed at all and this evidence suggested that **the load is transferred in a more physiological way from the stem to the femur without stress concentration.**

- *CF/PA 12 Composite*

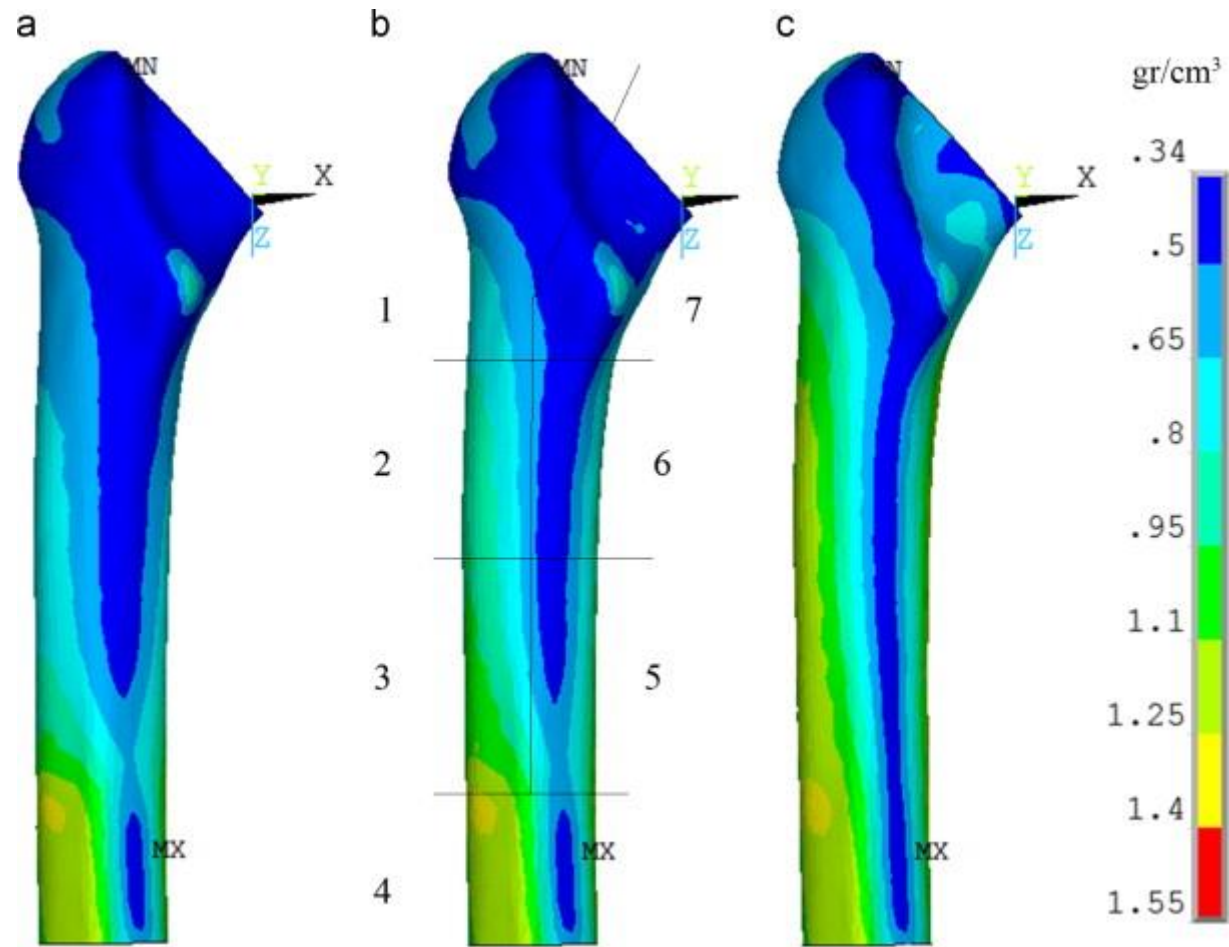
Other carbon fiber reinforced polymer composites have been shown as very promising biomimetic materials for orthopedic applications.

In particular, the study by Tavakkoli et al. investigated the CF/PA12 composite: this material is obtained by reinforcing a nylon 12 matrix with carbon fibers.

The properties of this composite material were compared with titanium and CoCrMo alloys.

Post-operative bone density and bone loss were assessed by FEA.

Authors found that the implant made with CoCrMo alloy, being the most rigid one, induced considerable stress-shielding (predominant bone density between 0.34–0.8 g/m³); on the other hand, the biomimetic CF/PA 12 material ensured a more homogeneous transmission of loads in the proximal region and consequently reduced the amount of bone reabsorption after implantation.



Bone density distribution after THA with (a) CoCrMo, (b) Ti alloy, (c) CF/PA12 composite hip implant

Experimental data collected with regard to the Gruen zones confirmed that the biomimetic composite can assure an amount of bone loss of 9%: this value is significantly lower than CoCrMo (27%) and Ti6Al4V (21%) alloys.

In particular, the Gruen zone 7 recorded the most significant bone loss for metal alloys, in agreement with the literature: 43% for CoCrMo and 35% for titanium alloy.

In the same portion, CF/PA 12 showed a bone loss of about 9%.

Moreover, standard deviation values of about 0.6% for the composite material confirm a much more uniform load distribution compared to metal alloys ($\sigma = 9.13\%$ for titanium alloy and $\sigma = 12.29\%$ for CoCrMo).

Taken together, the results of this study suggest that, in terms of bone remodeling, **the prosthetic implant made of CF/PA 12 showed significant advantages over metal alloys, ensuring lower stress-shielding effects and more contained and homogeneous changes in bone density.**

- *Other Design Solutions*

Recently, lattice and cellular structures have attracted the attention of many researchers from different fields, from bioengineering to aerospace engineering.

Thanks to the possibility to optimize the geometric distributions of strut size, pore morphology, and macroscopic apparent density, these structures can be suitable for improving bone regeneration and controlling the mechanical stimulus transferred from implant to bone.

Their fabrication requires non-traditional technologies: among the others, additive manufacturing allows achieving the precise fabrication and the tunable mechanical features of lattice structures with complicated topologies.

The term “**functionally graded materials (FGMs)**” has been proposed to indicate “advanced engineering materials designed for a specific performance or function in which a spatial gradation in structure and/or composition lend itself to tailored properties”.

Indeed, FGMs include a variety of materials, from ceramics to metals, from polymers to composites.

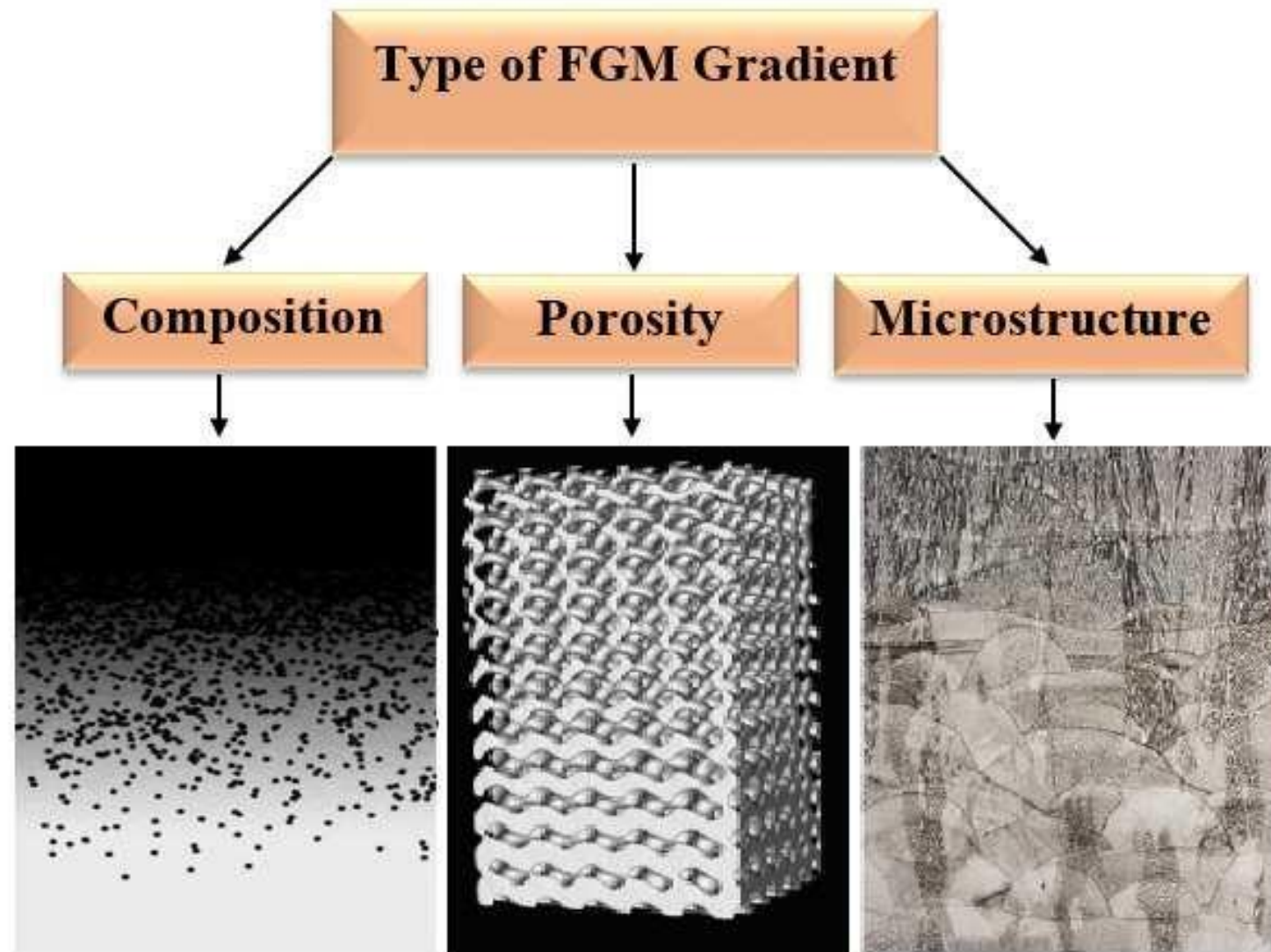
Generally speaking, FGMs try to mimic natural structures because these natural components have excellent features with respect to their specific application, whereas manmade parts are still far from them.



Surface treatments	<ul style="list-style-type: none">• Chemical and physical deposition• Thermal spray• Chemical modification• Plasma spray• Electrode/ion beam assisted deposition
Bulk treatments	<ul style="list-style-type: none">• Casting• Sedimentation• Solidification• Powder metallurgy• Sintering• Photopolymerization• Extrusion• Lamination• Powder bed fusion• Binder jetting• Material jetting

Examples of technologies for functionally graded materials (FGMs) production.

FGMs are emerging materials for orthopedic applications: **the gradual variation of their properties in space can reproduce the local properties of the native bone, minimizing the stress-shielding effect, at the same time reducing the shear stress between the implant and the surrounding bone tissue.**



With specific regard to the reduction of the stress-shielding effect, Mustafa G. Gok created and analyzed multi-lattice structures for the design of a hip stem implant made of Ti6Al4V.

The proximal part of the stem was divided into three regions: simple cubic, body-centered cubic, and face-centered cubic lattice structures were created on the upper part.

These multi-lattice designs caused a reduction of the maximum von Mises stress values on the prosthetic stem (from 289 to 189 Mpa), in parallel with a reduction of the weight (-25.89%).

Stress-shielding signals were obtained by determining the change in strain energy per unit bone mass caused by the presence of the femoral hip implant stem and its ratio to the intact bone.

In the case of hip-stems with multi-lattice designs, there was a significant increase (max. 150.47%) in stress-shielding signals from different zones of the femur: **the stress-shielding effect was significantly reduced thanks to multi-lattice designs.**

In general, two categories of cellular structures are considered: **stochastic** and **nonstochastic**.

The first ones are characterized by random variations in the shape and size of the cells; the second ones by the regular repetition of lattice structures.

Many are the papers published on both the structural characterization and the mechanical properties of FGMs, some of them regard the possibility to produce custom-made implants according to the data acquired from the patient via computed tomography (CT).

CT scan, along with a microstructural examination and mechanical testing, also allowed comparing various geometrical arrays of cellular, reticulated mesh, and open-cell foams with interconnected porosities for the production of the so-called “next-generation” biomedical implants: the variable density/porosity results in an optimized matching between the mechanical properties of the implant and the bone to reduce/eliminate the risks associated with the stress-shielding effect.

Conclusions and Future Perspectives

We can state that, on the one hand, the stress-shielding phenomenon has been deeply characterized and understood; on the other hand, **this phenomenon can be reduced but not completely circumvented.**

For sure, the recently proposed patient-specific approaches for designing and manufacturing tailored prosthetic systems can consider the individual characteristics of every single patient to provide them with the optimal implant solution.

In this perspective, it appears more and more evident that clinical and surgical competencies have to be technically supported by the contribution of the “engineering community”: mechanical engineers, materials engineers, bioengineers, computer science engineers, together they have to “create” a customized prosthetic device from patient’s CT or NMR images.

Currently available technical instrumentations and computational resources allow extending this approach and translating it into clinical practice.

As highlighted by Fontalis et al., patient-specific instrumentation (PCI) not only permits us to create customized devices, for example, by means of 3D printing technologies that can replicate the anatomy of the surgical site and the mechanical and structural characteristics of the bone and the prosthesis.

This approach has limitless applications in orthopedic surgery: it is currently restrained by the high costs and the lack of regulatory requirements.

Moreover, an extremely accurate pre-operative planning can be performed through new technologies like virtual reality (VR): it represents a very powerful tool to simulate the “real” surgery, allowing surgeons to train themselves in a “virtual” operating room on a “virtual” patient, who replicates the “real” one.

Recent technological advances also offer computer navigation systems and robotic-assisted surgery to guide the position of the cutting blocks and to perform the cut, respectively.

Taken together, these tools can generate a fundamental contribution in improving the precision of the surgical act and improve the match between patient's anatomy and prosthetic device to reduce the stress shielding effect.

Finally, it is worthy to mention the “ultimate goal” of hip arthroplasty: “generating a reproducible, durable, “forgotten” prosthetic hip”.