Mussel-Inspired Principle for Prosthesis Coatings

The number of people receiving artificial hip joints is increasing. Unfortunately, conventional prostheses often fail to adapt to the dynamic changes of the bone. They loosen and surgery is subsequently required. This problem may be solved by a biomimetic adhesive that supports ingrowth and enables permanent adhesion.

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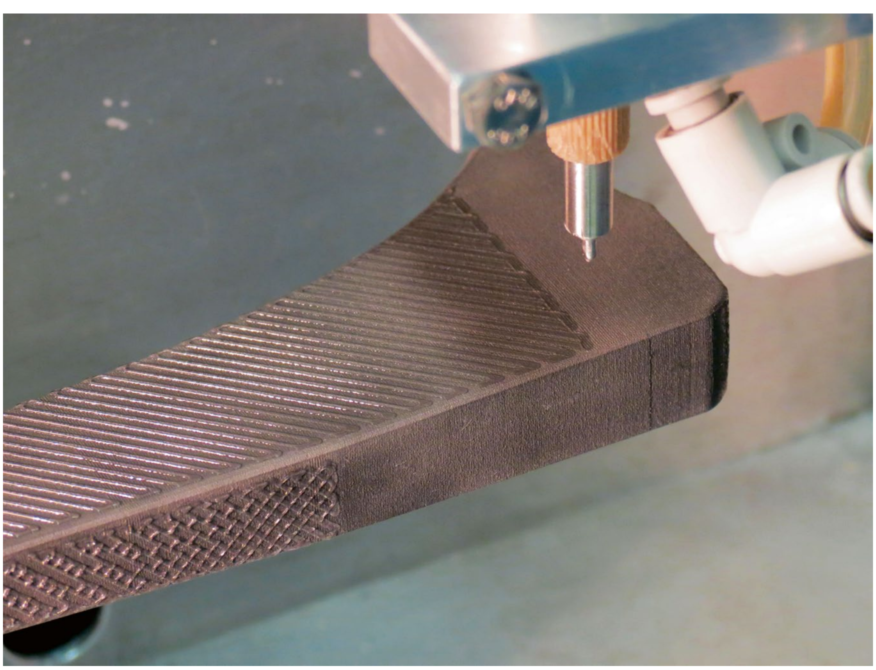
Demographic changes and an increase in life expectancy mean that more and more people are in need of a hip replacement. Conventional prostheses, however, have limitations – their adaptability to the dynamic changes of the bone is restricted, often resulting in loosening and, consequently, revision surgeries. In response to this challenge, researchers at the Fraunhofer Institute have pursued an innovative solution: an intelligent hip joint prosthesis with electronic components such as sensors and actuators. This allows continuous and non-invasive monitoring and adjustment, improving both the longevity and functionality of the prosthesis and reducing the need for surgical interventions.



Using 3D printing, the dopamine-based tissue adhesive is applied to a three-dimensional titanium stem of a hip joint.

The heart of this technology is a non-invasive procedure that determines prosthesis loosening by measuring the natural frequency of the biomechanical system. Using RFID technology, data on prosthesis vibrations are recorded and analyzed to ensure precise adjustments [1].

A synthetic, yet biomimetic coating

The development of the smart hip joint prosthesis revealed a significant gap in current implant technology. Improved initial fixation of the prosthesis to the bone maximizes its stability and promotes long-term integration. Against this backdrop, the Life Science and Bioprocesses research department at the Fraunhofer Institute for Applied Polymer Research IAP, with the participation of doctoral candidate Kathleen Hennig, derived the idea of a biomimetic adhesive that could revolutionize the connection between implant and bone. This adhesive is inspired by nature itself. It takes cues from the remarkable ability of mussels to adhere firmly to underwater surfaces. The adhesive aims to create immediate and permanent adhesion, supporting the ingrowth of the prosthesis and minimizing subsequent adjustments or revision surgeries.

Researchers first studied the unique biochemical properties of mussel proteins, and in particular the role of the amino acid DOPA in adhesion. They then developed a synthetic adhesive that mimics these natural principles. The scientists introduced dopamine-like monomers into a polymer framework, synthesizing an adhesive that not only exhibits strong adhesion properties, but is also biocompatible and versatile in medical applications. This breakthrough significantly improves the quality of life for patients with hip prostheses and represents a major advance in implant technology.

Enhanced stability and bone integration

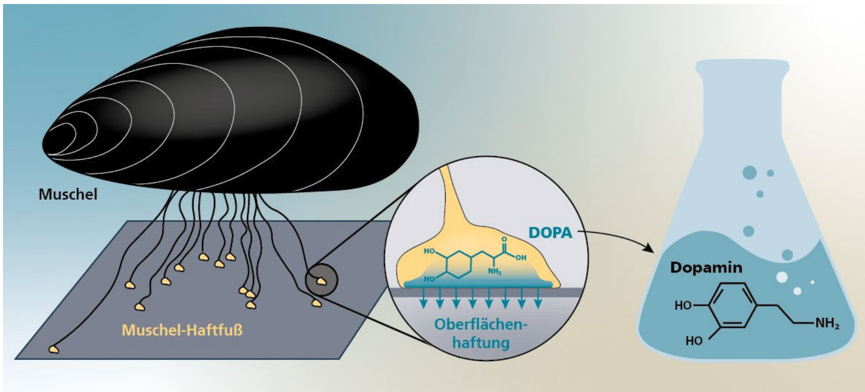
The challenge in using titanium for hip implants lies in its bioinertness: while the material is mechanically stable and biocompatible, it does not promote the growth of bone tissue, which can lead to a loose prosthesis over time. To counter this problem and ensure the long-term stability of the hip implant, researchers pursued a dual strategy. This strategy aims to modify the titanium surface to create a more attractive environment for bone cell attachment.
The project leaders developed an innovative 3D printing technology to create a specific microtopography on the titanium surface. This microstructure, consisting of dimensioned grooves, is particularly attractive to bone cells, which promotes the attachment and growth of bone tissue around the implant [2]. The ink for 3D printing consists of photochemically curable monomers, including acrylate derivatives, specially synthesized DOPA acrylate, hydroxyapatite nanoparticles, and other diacrylates (crosslinkers) [3]. The DOPA acrylate serves two functions. Firstly, it prevents the sedimentation of nanoparticles in the ink by arranging itself on their surface and optimizing their solubility. Secondly, it ensures strong binding of the coating to the titanium surface after curing.
The solid content of hydroxyapatite in the ink plays another biomimetic role: as the main component of bone, it helps the coating not only to appear "bone-hard", but also makes it potentially osteoconductive. This property promotes the growth and attachment of bone cells directly to the implant surface, thus significantly improving the long-term stability and integration of the implant in the body. Although this was not conclusively proven in the project, it led to further strategies in the overall composition of the ink [5].

Comparison with other prosthesis coating technologies

Various prosthesis coatings are employed to enhance the performance and longevity of implants. Among these, hydroxyapatite (HA) coatings are widely used due to their excellent biocompatibility and osteoconductivity [4]. HA coatings can be applied using different methods, including plasma spraying and high-velocity suspension spraying (HVSFS). Plasma spraying provides a robust coating but can suffer from uneven surface textures, whereas HVSFS allows for more controlled and uniform application, leading to better integration with the bone.
The surface roughness of prosthesis coatings significantly affects their performance. Studies have shown that increased surface roughness can enhance the initial stability and osseointegration of the implant. For instance, knee prostheses with rougher surfaces (average roughness Ra = 11.6 µm) demonstrated better functional outcomes and longer prosthesis survival compared to those with smoother surfaces (Ra = 5.0 µm). The rougher surfaces improve the bonding strength between the prosthesis and bone, reducing the incidence of aseptic loosening [7].
Biological functionalization of prosthesis coatings involves incorporating materials that promote better integration with the bone. Innovations in this field include the use of porous coatings like Porocoat and Gription, which mimic the natural bone structure and provide a scaffold for bone growth. These coatings offer enhanced initial stability and are particularly beneficial for younger patients who are more likely to require long-term implant solutions [8].

Future research directions

Future research could focus on further improving the biomimetic properties of prosthesis coatings. This includes the development of coatings that better mimic the natural bone environment, promoting faster and more reliable integration. Researchers are exploring the use of advanced materials, such as graphene



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Mussel glue is based on dopamine-containing proteins; the "DOPA" ensures excellent adhesive properties on surfaces.

and bioactive glass, which can offer superior mechanical properties and biocompatibility.

- **Smart Prostheses**

The integration of smart technologies into prosthesis coatings is another promising area. Embedding sensors and actuators within the coatings can allow for real-time monitoring of the implant's condition and automatic adjustments to improve stability and functionality. This approach can significantly reduce the need for revision surgeries and enhance patient outcomes.

- **Personalized Medicine**

Personalized approaches to prosthesis design and coating application are also gaining traction. Using advanced imaging and 3D printing technologies, it is possible to create customized implants tailored to the specific anatomical and physiological needs of individual patients. This personalized approach can improve the fit and performance of the prosthesis, leading to better overall outcomes.

- **Interdisciplinary Research**

Finally, interdisciplinary research combining materials science, biology, and clinical medicine is crucial for the next generation of prosthesis coatings. Collaborative efforts can lead to the development of innovative materials and techniques that address current limitations and open new avenues for implant technology.

Magnetic nanoparticles for future applications

Recent advancements in aerosol jet printing (AJP) and dual-material aerosol jet printing (DMAJP) technologies have opened new possibilities for integrating magnetic nanoparticles (MNPs) with polymeric materials. This method allows for the creation of magneto-responsive soft materials (our lab) with tailorable magnetic properties, suitable for various biomedical applications. The ability to locally control the composition of these materials during the printing process enables the production of small-scale, multi-material objects with programmable functions. Such advancements could lead to the development of semi-autonomous robots for medical applications, offering unprecedented capabilities in minimally invasive surgeries and targeted therapies [9].

By incorporating these sections, the article provides a comprehensive overview of current and future prosthesis coating technologies, offering valuable insights for researchers and practitioners in the field. //

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