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Original Research Article

Thermoplastic Polyurethane (TPU) Aligners from the Perspective of Bioengineering

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Abstract: This article explores the convergence between orthodontics and bioengineering, highlighting key advances in the use of biomaterials and technologies that are transforming orthodontic treatment. This review focuses on the innovative use of thermoplastic polyurethane (TPU) in invisible aligners highlighting its exceptional mechanical properties and addresses current challenges by proposing solutions focused on patient comfort, oral hygiene and preventing microbial proliferation. Regarding the latter, the contribution of nanotechnology is mentioned through the use of functionalized nanoparticles on the surface of the aligners, which could reduce the probability of oral bacterial infections. It also mentions how orthodontic archwires could be improved in anticipation of a future where orthodontics becomes more personalized and efficient. Undoubtedly, bioengineering and odontology are driving innovations together that will improve patients' quality of life.

Keywords: Alineador, Nanoparticulas, Nanotecnologia, Bioingenieria.

INTRODUCTION

In the field of healthcare, the constant search for new treatments and clinical therapies has driven innovation through the application of advanced technologies. In this context, bioengineering has positioned itself as a crucial discipline that brings significant solutions and advances to the health sciences. This synergy between engineering and biology has enabled the development of personalized therapies and the creation of innovative medical and dental devices that address today's therapeutic needs. Today, personalized medicine, personalized dentistry, and new technologies are revolutionizing the approach to patient care concerning their particularities. There is a need to explore how innovation in clinical therapy, bioengineering, and therapeutic needs associated with new technologies are shaping the future of health sciences.

Clinical inter, multi, and trans-discipline related to bioengineering promote collaboration and integration among different disciplines to provide more comprehensive, personalized, and patient-centered care. This makes it possible to use multiple perspectives to address health problems and ensure quality care.

Today, transdisciplinary approaches combining dentistry and bioengineering are recognized as an emerging field that combines the knowledge of the latter to improve results and efficiency in oral care. Materials engineering has been instrumental in developing new dental biomaterials, such as ceramics and polymers with improved strength, durability, and biocompatibility. This has enabled the development of more effective and aesthetic dental restorations, besides high-quality dental implants. Moreover, bioengineering enabled the design and production of customized and precise dental prostheses through 3D scanning, computational modeling, and computeraided manufacturing.

In addition, the processing of biomedical images from different imaging techniques such as computed tomography (CT), magnetic resonance imaging (MRI), and digital radiography has played a vital role in the field of dentistry by allowing to obtain detailed images of teeth, oral structures, and their possible pathologies. Thus, bioengineers and dentists can

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work together to develop dental prostheses and devices tailored to the patient's needs.

BACKGROUND

Orthodontics is a dental discipline dedicated to correcting irregularities in the alignment of the teeth and jaws. Ancient cultures such as the Egyptians, Greeks, and Romans attempted to address dental problems using rudimentary methods with limited results.

The real impetus for modern orthodontics came in the 20th century with the man considered the "father of orthodontics," Edward Angle. In the 1900s, Angle introduced fundamental principles and techniques that laid the foundation for contemporary orthodontics. Among his contributions were implementing brackets, bands, and wires to correct dental alignment.

As the century progressed, orthodontics continued to evolve. In recent decades, there have been notable technological advances and changes in treatment approaches. The introduction of new materials has improved the durability and esthetics of orthodontic devices.

In the last decades of the 20th century, the development of invisible orthodontics began and has been gaining popularity. Later, innovations such as Invisalign aligners, for example, and the improvement of 3D technology, have revolutionized treatment planning by allowing the creation of predictive digital models of the patient's mouth. This way, patients have been able to choose clear and removable aligners, providing a discreet and comfortable alternative to conventional methods.

Figure 1: Representative image of an invisalign aligner, source: Ourense, O. (2020, julio 22). *Ventajas y desventajas de los alineadores transparentes*. Ortodoncia Ourense. https://ortodonciaourense.com/ventajas-y-desventajas-invisalign/

Invisible aligners have revolutionized orthodontics by offering a discreet and aesthetically appealing alternative. These devices, made of a clear polymeric material, are customized for each patient through digital three-dimensional scanning, allowing for accurate and predictive treatment planning. Their removability facilitates brushing, flossing, and eating without specific restrictions. Digital technology not only allows precise tracking of progress but also reduces the need for frequent appointments.

Although not suitable for all cases, invisible aligners have gained popularity over traditional orthodontic methods [1].

Orthodontics and Aligner Technology

Orthodontics has undergone a significant evolution in the materials used over time. From the first devices made of metal wires and bands, progress has been made toward the design of smaller and lighter brackets. The application of digital technologies, such as intraoral scanners and computer-aided design, has improved the accuracy and efficiency of the process. As mentioned, the advent of clear aligners made of thermoplastic materials has allowed for more aesthetic and comfortable treatments. Meanwhile, research continues on biomaterials to further improve the biocompatibility and force transmission efficiency of these devices, contributing to advanced and personalized orthodontics.

Biocompatibility

Bioengineering, or more specifically, biomaterials science, has been faced with the need to search for and develop materials that can be in direct contact with the human body and living tissues without causing any harm. These biomaterials must be biocompatible or bioinert, depending on whether there is interaction with the organism. Biocompatible materials can be metals, ceramics, or polymers. The most important characteristic is that they do not cause harm or cause rejection by the human body [2].

The qualities of a biocompatible material are listed below:

A. Not producing an immune system response
B. Non-toxic
C. Not carcinogenic

D. Not medically incompatible
E. Not hemodynamically incompatible

Biocompatibility is the biological acceptance of materials by the tissues of living organisms at various levels, such as material/tissue, mechanical factors, and reaction to degradation [2].

Biocompatibility plays a crucial role in the selection of materials for orthodontic devices, such as removable aligners. In other words, the materials used must be safe for prolonged contact with oral tissues, being careful to avoid allergic reactions or irritation. Certain medical-grade thermoplastic materials, such as polyurethane or polyethylene, are commonly used because of their biocompatibility.

In terms of clinical effectiveness, the choice of material directly affects the ability of the device to apply controlled and directed forces. Materials must be flexible enough to allow for tooth movement and must also maintain the necessary rigidity to achieve specific changes. Innovations in advanced thermoplastic materials allow for precise application of forces, contributing to more predictable and efficient clinical outcomes.

In addition, the material's texture, weight, and adaptability influence patient comfort. Removable aligners, being made of materials that are light and soft to the touch, minimize discomfort and ulceration. Furthermore, the ability to remove the aligners during feeding and oral hygiene significantly improves the patient experience compared to fixed devices.

Removable orthodontic aligners have undergone remarkable advances in recent years regarding their materials and manufacturing methods. In 1940 the devices were less sophisticated and comfortable than today's versions, made of simple plastics and limited in aesthetics and efficiency. Today, however, removable aligners are manufactured with high-tech thermoplastic polymers, such as polyurethane and high-density polyethylene, which offer flexibility, transparency, and strength for extended wear. In addition, 3D scanning technology has revolutionized their fabrication, allowing orthodontists to obtain accurate digital models of the patient's teeth through intraoral scans, eliminating the need for physical impressions. Computer-aided design (CAD) and computer-aided manufacturing (CAM) allow precise and predictive customization of aligners for each patient.

In the future, we can expect the development of even more advanced aligner materials that are durable, elastic, comfortable, and have some bioactivity similar to that of the oral cavity.

Mechanical Properties of Thermoplastic Polyurethane (TPU)

Thermoplastic polyurethane (TPU) exhibits exceptional mechanical and physical properties that distinguish it as a versatile polymeric material. As to its mechanical properties, TPU stands out for its remarkable flexibility and elasticity, making it ideal for applications requiring impact resistance and resilience. It is also highly wear-resistant, durable, and able to maintain its properties even under adverse conditions. Chemically, TPU shows good resistance to various chemicals, oils, and solvents, making it a robust choice in industrial environments [12].

Concerning its physical properties (see Table 1), TPU can offer transparency, making it suitable for applications requiring visual clarity, such as protective films. In addition, it exhibits weather resistance, ensuring that it maintains its physical properties under varying environmental conditions. TPU's low density contributes to its lightweight. Its dimensional stability is outstanding, retaining shape and dimensions under various conditions.

TPU generally shows good resistance to water absorption, favoring its performance in wet environments. These properties make TPU a material of choice for multiple applications, demonstrating its versatility and adaptability in various industrial sectors [3].

Table 1: Mechanical properties of TPU (ref)

Mechanical properties	Typical value
Tensile elasticity modulus	26 MPa
Tensile stress at deformation	8.6 MPa
Tensile stress at break	39 MPa
Elongation at deformation	55%
Elongation at break	580%
Bending modulus	78.7 Mpa

TPU as a specific material is gaining relevance in orthodontics. Its Young's modulus (flexibility) and other properties make it suitable for the development of technologically advanced aligners. In addition, TPU is one of the most versatile engineering thermoplastics as it possesses elastomeric properties: it has a high tensile modulus compared to rubber, high abrasion resistance, and high wear and breakage resistance [4].

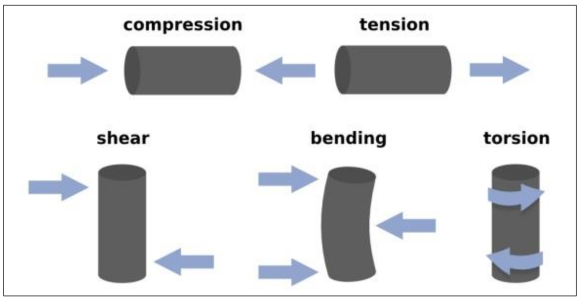

Figure 2: Representative image of the types of mechanical stress in a body, source: *Internal forces (stress)*. (s/f). Purduesigbots.com. Recuperado el 4 de diciembre de 2023, de. https://wiki.purduesigbots.com/hardware/designfundamentals/internal-forces-stress

The biomechanics of mastication involve an intricate interplay of musculoskeletal structures and applied forces that ensure the efficient grinding of food. Masticatory muscles, such as the temporalis, masseter, and pterygoid, play a key role in generating the necessary force to execute jaw elevation, depression, and lateral movements. During this process, the forces applied vary according to food consistency, and are carefully distributed to avoid excessive stress on the jaw structures. The Temporomandibular Joint (TMJ) contributes significantly, allowing smooth and coordinated movements. The proper shape and position of the dentition are also crucial to facilitate efficient chewing and ensure an even distribution of forces. Any imbalance in these biomechanics can trigger temporomandibular disorders and affect oral health [11].

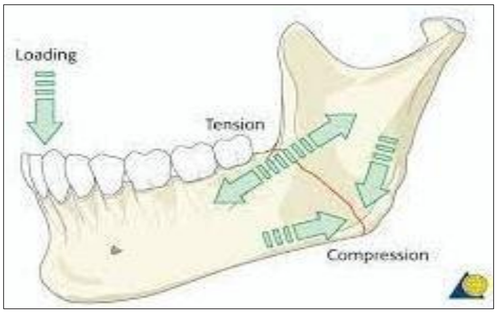

Figure 3: Representative image of the types of mechanical stress in the human jaw, Source: *Mecánica de la Mandíbula Inferior*. (s/f). Docsity.com. Recuperado el 4 de diciembre de 2023, de https://www.docsity.com/es/mecanica-de-la-mandibula-inferior/5186738/.

Invisible orthodontic aligners made of transparent materials eliminate the need of wires and brackets, which allows them to offer a discreet and comfortable appearance. As they are removable, they facilitate oral hygiene and allow an unrestricted diet.

The digitized manufacturing process, applying technologies such as 3D printing, expands its potential as an orthodontic device. In addition, its smooth design with no protruding parts improves comfort. Discreet treatment with aligners involves gradual changes, making modifications less obvious than those performed with traditional orthodontic methods. However, the patient must maintain good oral hygiene, since biofilm generation remains the same with the use of orthodontic aligners, despite allowing better oral cavity cleaning compared to other devices such as archwires or brackets.

Currently, orthodontic treatment has become more accessible in the market, which offers various methods or techniques to solve malocclusions and skeletal discrepancies, so much so that demand has increased in all age groups [5]. Fixed appliances, conventionally known for years, have given good results and are the most widely used treatment method. However, when brackets, bands, tubes, and extra attachments are placed inside the oral cavity, they often hinder the proper removal of plaque, and facilitate the retention of biofilm in the stomatognathic system [6]. A higher rate of dental plaque promotes enamel demineralization and subsequent gingival inflammation. A deficiency of oral health can lead to periodontal disease [7].

The study conducted by Rossini determined that orthodontics with removable thermoformed plates gave positive results in connection with periodontal status versus conventional fixed brackets in the oral cavity. The researchers conducted a meta-analysis and determined that periodontal health was better with the use of removable thermoformed plates than with the conventional fixed appliance treatment [8].

On the other hand, Azaripour and his team analyzed 100 patients (50 with fixed appliances and 50 with Invisalign® aligners) over six months. They found that the patients' conventional fix devices directly interfered with periodontal health because they worsened their oral hygiene status. However, plaque accumulation was virtually the same in both the Invisalign® and fix appliance groups. The conclusion was that the Invisalign® patients had much better periodontal health, while the hygiene techniques did not differ between the two groups [9].

On the other hand, Levrini *et al.*, with a sample of 77 patients divided into three groups (Invisalign® group, another with fixed devices, and the third as a control group), evaluated parameters such as probing depth, plaque index, and bleeding on probing. The researchers obtained data similar to those obtained by Azaripour: aligners with Invisalign® show fewer periodontal adverse effects compared to the fixed orthodontic appliance group; they concluded that thermoformed plates represent the first therapeutic option in periodontally compromised patients [10].

Orthopedic Bioengineering Trends

Current trends in orthopedic bioengineering reflect an increasingly personalized and technological approach. Technological advances have played a crucial role in this field, such as using thermoplastic polyurethane (TPU). Today, we are seeing greater integration of additive manufacturing techniques, such as 3D printing, which allows for the creation of customized, patient-specific orthopedic devices. The ability of TPU to adapt anatomically to the patient's body, combined with its strength and lightweight, has significantly improved the quality of life of people requiring such devices.

Moreover, orthopedic bioengineering is experiencing advances in the integration of sensors and intelligent devices in prostheses, allowing more precise and natural control of movements. These technological innovations not only improve the functionality of orthopedic devices but also open up new possibilities for rehabilitation and remote patient monitoring.

Current Challenges of TPU in the Orthodontic Field

Contemporary orthodontics faces several challenges. Bioengineering, specifically in biomaterials, is innovating in materials such as thermoplastic polyurethane (TPU), but also from the point of view of biomechanics, image processing, digital flow, and 3D printing.

One of the common problems associated with traditional orthodontic devices is the discomfort caused by brackets and wires. This is where the introduction of materials such as TPU, with its wellknown flexibility and adaptability, offers a more comfortable alternative. TPU orthodontic aligners are less intrusive and provide greater patient comfort. In addition, their durability contributes to greater longterm effectiveness.

On the other hand, bioengineering has allowed advances in the manufacture of customized devices using 3D printing techniques which speed up the process and can also reduce the duration of treatment. The ability of TPU to adapt anatomically to the tooth structure contributes to precision in the correction of malocclusion.

As for oral hygiene, this is a critical aspect that bioengineering seeks to address through the development of polymeric biomaterials and the creation of orthodontic devices that are easier to clean and maintain in good condition. Biosafety and biocompatibility of TPU are essential in this context.

Additionally, the integration of technologies such as artificial intelligence and remote monitoring into orthodontic devices can improve treatment efficiency and provide dental health professionals with greater visibility into patient progress.

Opportunity Areas in Customized Dentistry

New trends in orthodontic devices are incorporating technological advances to improve treatment efficacy and patient comfort. One of these trends is the use of aligners functionalized with nanoparticles. These aligners can be impregnated or coated with nanoparticles that possess antibacterial and antiinflammatory properties. This not only contributes to maintaining better oral health during treatment but also reduces the risk of oral hygiene-related complications.

Another notable innovation is the functionalization of orthodontic archwires. Although they are part of traditional braces, they can now be designed with advanced materials or special coatings to give them better biomechanical properties. Some functionalized archwires aim to apply smoother and more constant forces, thus reducing discomfort and speeding up the dental alignment process. Materials that respond to specific stimuli, such as temperature or pressure, are also being explored to achieve a more precise adaptation to the patient's dental anatomy.

In addition, the integration of sensors and monitoring technology into orthodontic devices is a growing trend. These sensors can collect data on pressure exerted, tooth position, and other relevant parameters. Orthodontic professionals can use this information to adjust and customize treatment, offering a more individualized approach.

Artificial intelligence is also playing a paramount role in emerging trends. Machine learning algorithms can analyze large data sets to predict treatment progression and optimize treatment plans, which could lead to greater efficiency and more predictable outcomes.

These trends in orthodontic devices are transforming orthodontic practice, improving patient experience, shortening treatment times, and allowing a more personalized and precise approach to correcting dental malocclusion.

CONCLUSION

In conclusion, bioengineering applied to orthodontics has marked a significant milestone in the evolution of dental treatment, providing more personalized, comfortable, and efficient solutions. The synergy between engineering and dentistry has allowed the development of innovative devices and techniques that address current therapeutic needs and improve the patient's quality of life.

The introduction of advanced materials such as thermoplastic polyurethane (TPU) has revolutionized orthodontics by offering exceptional mechanical properties, flexibility, and anatomical adaptability. TPU invisible aligners represent an aesthetic and comfortable alternative to traditional methods, promoting oral hygiene and reducing the discomfort associated with brackets and wires.

The evolution of orthodontics is not limited to materials alone but encompasses the integration of technologies such as 3D printing, artificial intelligence, and monitoring sensors. These innovations allow for more precise, personalized, and efficient treatments. In addition, the application of nanoparticles in aligners and the functionalization of orthodontic archwires indicate growing attention to oral health during treatment.

The crucial role of bioengineering extends beyond aesthetics and comfort, addressing fundamental challenges in orthodontics, such as oral hygiene, biocompatibility, and clinical effectiveness. Interdisciplinary collaboration between bioengineers and dentists has allowed overcoming barriers and moving towards a more holistic and patient-centered approach.

In the future, the outlook is promising towards opportunities with even more advanced biomaterials, continued integration of emerging technologies, and increased customization of treatments. Orthodontic bioengineering, in addition to transforming clinical practice, redefines patient experience, highlighting the importance of continuous innovation in oral health care.

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