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Smart Brackets in Orthodontics: Bridging Digital Innovation and Clinical Practice

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ABSTRACT
The integration of sensing, wireless communication, artificial intelligence (AI) and digital health technology with orthodontic appliances is driving the development of real-time monitoring systems for orthodontic treatment. Telemetric smart brackets represent an emerging technological approach for orthodontic diagnosis and treatment monitoring. Conventional orthodontic appliances apply mechanical forces to facilitate controlled tooth movement; however, clinicians typically have limited access to real-time information regarding the forces and moments acting on individual teeth. Telemetric smart brackets aim to overcome this limitation by incorporating miniaturized sensors, microelectronic components, wireless communication systems and computational algorithms into orthodontic appliances. These innovations may enable continuous monitoring of orthodontic forces, tooth movement, oral hygiene and overall treatment progress. This review highlights recent advances in orthodontic sensors, wireless connectivity, power sources, clinical applications and Internet of Dental Things (IoDT) integration, while also addressing current limitations and future directions.

Keywords: smart brackets; telemetric orthodontic appliances; orthodontic force measurement; real-time monitoring; intraoral sensors; artificial intelligence.

1. INTRODUCTION

Effective orthodontic treatment depends on the controlled application of appropriate forces to achieve desired tooth movement while minimizing adverse effects such as root resorption, loss of anchorage and prolonged treatment duration. Since this process usually spans a long period, patients require regular appointments and reinforcement of oral hygiene instructions.[1,2] However, conventional approaches are constrained by relatively infrequent visits and reliance on subjective patient reports which may fail to capture ongoing changes in real time. As orthodontics increasingly moves towards patient-focused care and digital integration, the need for improved monitoring of treatment progress has become more evident. Tele-orthodontics may address this by reducing the routine in-person visits, enhancing patient-clinician communication and better tracking adherence during prolonged therapies.

The Internet of Things (IoT) refers to an interconnected network of physical devices equipped with sensors and communication capabilities that enables the collection, exchange and processing of data. In dentistry, the Internet of Dental Things (IoDT) applies this concept to oral healthcare, with potential applications in treatment monitoring, risk assessment and early detection of oral conditions such as dental caries and periodontal disease. Nanotechnology has also advanced considerably across multiple disciplines with major developments seen in electronics. Nanoelectronics focuses on designing electronic components at the nanoscale to reduce device size, improve efficiency and lower power requirements. These advances have recently attracted interest in orthodontics, particularly for their potential use in developing next-generation orthodontic brackets with integrated sensing and monitoring capabilities.

2. SMART BRACKETS

Smart orthodontic brackets are an emerging technological development in orthodontics. Unlike conventional brackets used in fixed appliance therapy, these brackets incorporate sensors and digital functions that allow improved monitoring and management of treatment progress. Their primary objective is to provide more quantitative information regarding orthodontic treatment and potentially support more predictable tooth movement. These brackets may facilitate regulation of the direction, magnitude and rate of tooth movement. Key features commonly associated with these systems include real-time data tracking, wireless communication with external devices such as smartphones or computers, continuous data collection and tools that improve patient engagement and compliance.[3]

Experimental systems have incorporated embedded micro-sensors to detect orthodontic forces and provide quantitative biomechanical information during treatment. Most of these sensors are based on piezoresistive, strain-gauge or Complementary Metal Oxide Semiconductor (CMOS) technologies which convert mechanical deformation produced by orthodontic forces into measurable electrical signals.[4-9] Depending on the design, the collected data may be processed and transmitted wirelessly to a digital interface, potentially allowing clinicians to assess the magnitude and direction of forces acting on individual teeth.

Recent research has focused on improving sensor sensitivity, accuracy, miniaturization and wireless data transmission.[10] Experimental multi-sensor microchips have demonstrated the feasibility of three-dimensional measurement of orthodontic forces and moments, although variability in wire-bracket interaction may influence measurement accuracy.[10] Innovations in this field include ceramic bracket systems incorporating CMOS-based sensors and micro-coils for wireless data transmission. Related intra-oral sensing technologies have also been explored in clear aligners including semi-spherical elastic sensors for force measurement.[6,8]

3. DESIGN PRINCIPLES

3.1 Types of sensors

Smart orthodontic brackets rely on miniaturized sensing technologies to detect and quantify treatment related biomechanical parameters. Micro-electro-mechanical systems (MEMS) technology has enabled the development of compact sensors suitable for integration into small biomedical and intraoral devices. Depending on the intended application, sensing systems may be designed to detect mechanical forces, strain, pressure, temperature or other treatment-related parameters.[11]

Complementary Metal Oxide Semiconductor (CMOS) technology has been investigated for the development of miniaturised force-sensing systems in orthodontic brackets. One reported approach involves integrating a miniaturized CMOS stress sensing chip into an orthodontic bracket to detect mechanical stresses generated by the interactions between the arch wire and bracket.[6] In piezoresistive systems, mechanical deformation produces changes in the stress distribution within the silicon-based sensing elements. The sensing principle is based on the piezoresistive properties of silicon. Multiple piezoresistive sensing elements positioned within the CMOS chip convert these mechanical changes into electrical signals which can substantially be calibrated and processed to estimate the applied orthodontic force-moment system.[12]

3.2 Signal Acquisition & Wireless Communication

Smart orthodontic systems require efficient acquisition and transmission of signals generated by intraoral sensors. Depending on the sensor design, these signals may represent mechanical parameters such as force, strain, pressure or other treatment-related variables. Wireless communication technologies have been investigated for transmitting data between intraoral devices and external receivers. Ultra-wideband (UWB) and intrabody communication (IBC) have been explored as short-range, low-power communication approaches for interconnecting sensors and devices located on, within or near the human body.[13,14] Bluetooth Low Energy (BLE) and Near Field Communication (NFC) have also been investigated for communication between smart orthodontic devices and external digital platforms.[15] The selection of a communication protocol depends on factors such as transmission range, power consumption, data rate, device size and the requirements of the intended clinical application.

3.3 Telemetric Data Transmission

Following wireless transmission, the acquired sensor signals can be demodulated, digitized, processed and transferred to a clinical software interface for interpretation. The processed data can be converted into quantitative biomechanical parameters and presented through digital platforms for clinical assessment.

Artificial intelligence-based analytical approaches may further assist in interpreting sensor-derived data and identifying patterns related to treatment progress. However, the ability of such systems to accurately predict individual tooth movement or determine optimal orthodontic adjustments remains investigational and requires further validation.[8]

4. CLINICAL APPLICATIONS

4.1 Real-Time Force Monitoring

Real-time force monitoring is a potential clinical application of smart orthodontic brackets. In force-sensing systems, mechanical deformation associated with loading of the bracket and archwire can be detected by embedded sensors and converted into measurable electrical signals. Experimental systems have demonstrated the ability to quantify orthodontic forces and moments with high sensitivity; one reported system achieved a force resolution of approximately 60 mN and a torque resolution of 0.14 N mm.[8] Such measurements may provide clinicians with quantitative information regarding the magnitude and distribution of orthodontic forces acting on individual teeth. However, the clinical benefits of continuous force monitoring and its potential to reduce adverse effects such as root resorption, unwanted tooth movement or periodontal complications require further clinical validation.

4.2 Treatment Optimization

Force-monitoring data may complement computational models and artificial intelligence (AI)-based analytical approaches to support individualized orthodontic treatment planning. Quantitative information regarding the biomechanical conditions associated with tooth movement may help clinicians identify deviations from the intended treatment response and make more informed treatment modifications. Depending on the design of the sensing system, smart orthodontic appliances may also monitor parameters such as three-dimensional force and moment components, pressure, strain, temperature, appliance wear time and bracket debonding.The resulting data can be presented through digital platforms as numerical measurements, graphical displays, alerts or longitudinal treatment trends. Quantitative assessment of three-dimensional orthodontic force-moment systems is important for understanding the biomechanics of therapeutic tooth movement and may contribute to improved treatment predictability and reduction of undesirable effects.[12] However, whether smart sensing systems can directly improve treatment efficiency or shorten treatment duration remains to be established through well-designed clinical studies.

4.3 Patient Compliance

Telemetric smart brackets integrated with digital or mobile applications may support treatment adherence by providing timely and personalized feedback during orthodontic treatment. Depending on the system design, detection of bracket debonding may enable prompt notification and facilitate early communication with the orthodontic team, potentially reducing treatment disruption. Related intraoral sensing technologies, such as pH sensors, may provide information about the oral environment and could help reinforce oral hygiene awareness through periodic monitoring.Digital appointment reminders may further support treatment adherence. Evidence suggests that reminder systems can improve patient attendance.[16] In addition, smartphone-based interventions have been reported to improve oral hygiene-related outcomes, including plaque and gingival indices, among orthodontic patients.[17] Digital communication platforms may also facilitate patient-orthodontist communication and encourage active participation in treatment. To minimize information overload, patient-facing interfaces should present concise, clinically relevant information rather than complex diagnostic data, thereby supporting clearer communication and reducing the potential for misinterpretation.

5. TECHNOLOGICAL ADVANCES

5.1 Sensor Miniaturization

Sensor miniaturization is an important technological development that facilitates the incorporation of sensing capabilities into orthodontic appliances while maintaining their compact size and patient comfort. Advances in microelectromechanical systems (MEMS), microfabrication, flexible electronics and low-power electronic technologies have enabled the development of increasingly compact sensing platforms.[18,19] In smart orthodontic brackets, miniaturized sensors may be incorporated within or adjacent to the bracket to monitor treatment-related parameters without substantially altering the size or design of the appliance. Further advances in miniaturized and flexible sensing technologies may facilitate their integration into orthodontic brackets and other intraoral appliances while maintaining patient comfort and esthetics.

5.2 Energy Harvesting

Energy harvesting has been explored as a potential alternative to conventional batteries for powering miniaturized intraoral and orthodontic sensing devices. Piezoelectric and thermoelectric approaches can potentially harvest energy from mechanical deformation associated with oral activities, such as chewing or from temperature gradients within the oral environment. One reported study used an electrospun polyvinylidene fluoride/zirconium dioxide (PVDF/ ZrO_2) composite membrane to develop a biocompatible force sensor for bite-force monitoring, demonstrating the potential of energy-harvesting materials for self-powered intraoral sensing applications.[20]

6. LIMITATIONS AND CHALLENGES

Despite the potential of smart orthodontic technologies, several limitations currently restrict their widespread clinical translation. One of the major challenges is the relatively high cost associated with the advanced smart bracket systems. Sophisticated manufacturing processes, specialised electronic components, software and digital fabrication infrastructure may increase production and treatment costs potentially limiting accessibility in routine orthodontic practice.[4,21] Biocompatibility and long-term safety are also important considerations, particularly for systems incorporating nanoparticles or electronic components. The effects of nanoparticle incorporation on surface characteristics, bacterial adhesion, mechanical properties and the physicochemical behaviour of bracket materials require careful evaluation.[3,22] Although nanomaterials may offer desirable surface or mechanical properties, their biological effects depend on factors such as particle composition, size, concentration, surface characteristics and potential release into the oral environment. Therefore, comprehensive biocompatibility assessment, standardised testing and appropriate regulatory oversight are necessary before widespread clinical adoption.[23]

Smart brackets introduce additional challenges related to the reliability and durability of embedded electronic components. Sensors must withstand repeated mechanical loading, moisture, temperature fluctuations, chemical exposure and other conditions encountered in the oral cavity without compromising their sensing performance. Miniaturised components must also be adequately protected and integrated without adversely affecting bracket strength, dimensions, patient comfort or oral hygiene. Sensor failure, loss of calibration or deterioration in signal quality could reduce the reliability of the collected data. Additional clinical procedures and costs may be incurred if component replacement or bracket replacement is required.[4,24] Wireless communication and power management represent further technical challenges. Signal interference, limited transmission range, power consumption, battery requirements and difficulties in maintaining reliable communication within the oral environment may affect system performance. Integration with existing digital orthodontic workflows also requires appropriate software, data-management systems and interoperability between devices and platforms. In addition, clinicians may require training in digital treatment planning, data interpretation and digital fabrication to ensure appropriate use of these technologies.[25] Well-designed in vitro, in vivo and clinical studies are required to establish the safety, reliability and clinical effectiveness of these technologies before their routine implementation in orthodontic practice.

7. FUTURE DIRECTIONS

Future development of smart orthodontic brackets is likely to focus on improving sensing accuracy, device miniaturisation, biocompatibility, digital integration and patient-specific treatment monitoring. Progress in biomaterials, flexible electronics, sensor technology, wireless communication, artificial intelligence (AI) and digital fabrication may facilitate the development of increasingly integrated orthodontic appliances. However, translation of these technologies into routine clinical practice will require interdisciplinary collaboration and robust clinical validation. For smart bracket systems, future research should prioritise standardised sensor calibration, reproducibility of force and moment measurements, long-term sensor stability and validation under clinically relevant intraoral conditions. Development of common testing protocols would facilitate meaningful comparison among different sensing platforms and improve the reproducibility of previous research experiments. Integration with orthodontic software and digital clinical workflows should also be improved to enable efficient acquisition, storage, visualisation and interpretation of sensor-derived data. AI-based analytical methods may further assist in identifying clinically relevant patterns within these datasets; however, their performance should be evaluated prospectively against established clinical measures before they are incorporated into routine decision-making. Patient data governance will become increasingly important as orthodontic systems incorporate wireless communication, cloud-based platforms and AI-assisted analysis. Future development should therefore incorporate appropriate approaches to data privacy, cybersecurity, informed consent, data ownership and secure transmission from the design stage. Interoperability between intraoral devices, imaging systems, electronic health records and orthodontic software may also be necessary for effective implementation within digital clinical workflows.

Ultimately, future research should move beyond demonstrating technological feasibility toward establishing clinical effectiveness, safety, reliability, cost-effectiveness and patient acceptability. AI and other digital technologies should function as supportive tools that complement, rather than replace, professional clinical judgement. Well-designed prospective clinical trials, long-term follow-up studies, standardised testing protocols and interdisciplinary research will be essential to determine whether smart orthodontic brackets can provide meaningful advantages over conventional orthodontic systems.

8. CONCLUSION

Smart brackets may support more individualized treatment monitoring and data-informed clinical decision-making. However, these bracket systems remain at the experimental or early developmental stage and evidence regarding their long-term reliability, biocompatibility, clinical effectiveness, cost-effectiveness and integration into routine orthodontic practice remains limited. In particular, the clinical value of continuous telemetric force monitoring is yet to be established through adequately designed prospective clinical studies. Therefore, smart brackets should currently be regarded as a promising emerging technology rather than an established replacement for conventional orthodontic appliances.

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