Yassine BENSMAIL

A glimpse into the future with Orthodontics' Smart Brackets

Universidade Fernando Pessoa

Faculdade Ciências da Saúde

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Trabalho apresentado à Faculdade de Ciências da Saúde

da Universidade Fernando Pessoa como parte dos requisitos

para obtenção do grau de Mestre em Medicina Dentária.

Yassine BENSMAIL

RESUMO

O aparelho ortodôntico fixo tipo multibandas atual não permite medir ‘in-vivo’ as forças e torques aplicados ao dente individual. Para um tratamento ideal e para reduzir os efeitos iatrogênicos, o ‘Smart Bracket’ foi desenvolvido para uma próxima geração de aparelhos ortodônticos fixos fornecendo ao ortodontista uma medida quantitativa sobre as forças e torques aplicados a cada dente ao longo da terapia.

O presente trabalho pretende ser uma revisão narrativa da literatura tendo como objetivo descrever o conceito de ‘Smart Bracket’, comparando-o com os aparelhos ortodônticos fixos atuais. Além disso, procura analisar e resumir o seu desenvolvimento e a evolução dos seus vários protótipos existentes.

A pesquisa foi realizada entre Fevereiro e Agosto de 2020 por meio do motor de busca B-On (entre outros), para o período temporal 2005-2020, com o objectivo de sintetizar a literatura sobre o sistema, identificar seus limites e, eventualmente, recomendar novos temas de pesquisa. Adicionalmente, artigos de revisão e livros científicos foram consultados a partir de 2000 para apresentar os atuais aparelhos multibandas e seus efeitos iatrogênicos.

Palavras-chave: "Braquetes Ortodônticos"; "Torque"; "Reabsorção da Raiz"; "Tensão Mecânica"; "Calibração"; "Tecnologia sem Fios" e "Dispositivo de Identificação por Radiofrequência"

ABSTRACT

The current multi-bracket appliances do not allow to measure 'in-vivo' the forces and torques applied to the individual tooth. For an ideal treatment and to reduce iatrogenic effects, the 'Smart Bracket' has been developed for a next generation of fixed orthodontic appliances providing the orthodontist with quantitative measure of the forces and torques applied to each tooth throughout therapy.

The present work intends to be a narrative review of the literature aiming to describe the concept of 'Smart Bracket', comparing it with the current fixed orthodontic appliances. In addition, it seeks to analyze and summarize its development and the evolution of its various existing prototypes.

The literature research was carried out between February and August 2020 using the search engine B-On (among others), for the period 2005-2020, with the aim of synthesizing the literature on the system, identifying its limits and, eventually, recommend new research topics. In addition, review articles and scientific books were consulted from 2000 onwards to present the current multiband devices and their iatrogenic effects.

Keywords: "Orthodontic Brackets"; "Torque"; "Root Resorption"; "Stress, Mechanical"; "Calibration"; "Wireless Technology" and "Radio Frequency Identification Device".

DEDICATION

I could not find in the dentistry field better than Dr. Ayoub BENHARIGA,

I dedicate this thesis to you my dear friend,

You, who was a source of my quest for excellence

You, the generous, who likes to share knowledge unceasingly, without the slightest information retention.

You, who gave me the taste to love the profession of dentist very early on, which has become a real pleasure for me.

You, the humanist, an exceptional man of remarkable intelligence who is a source of inspiration to many people, I encourage you to continue your excellent and fruitful work

It is with my sincere gratitude that I thank you my dear friend.

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For doing me the honour of directing and supervising this thesis. For your availability, your advice and your encouragement which made it possible. Please find in this work the expression of my deep respect.

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My lovely wife Nesrine thank you for being so patient with me and for giving me unconditional love and happiness.

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I would like to thank all my friends, that I cannot name them all because there are so many. Who are from France, Portugal, Algeria, Tunisia and Vietnam…

For my employers Catherine and Thierry who have exceptional human qualities, for whom I have a particular affection and friendship.

Finally, to Fernando Pessoa University and to all the professors, for allowing me to accomplish this wonderful work, and for giving me the chance to realize my project.

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INDEX OF ABBREVIATIONS AND ACRONYMS

3-D	Three-dimensional
6DOF	Six degrees of freedom
ADC	Analog-to-Digital Converter
Au	Gold
CMOS	Complementary Metal Oxide Semiconductor
Cu	Copper
F	Force
F/T	Force/Torque
FEA	Finite Element Analysis
FET	Field effect transistor
FMT	Force-Moment Transducer
IC	Integrated Circuit
IEEE Xplore	Institute of Electrical and Electronics Engineers web search engine
IMTEK	Institut für Mikrosystemtechnik
ISM-band	Industrial, Scientific, and Medical frequency bands
Mesh	Medical Subject Headings
MNE	Micro/Nano- Electronics
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor
MUX	Multiplexer
NMOS	N-type/Negative Metal–Oxide–Semiconductor
OSIM	The Orthodontic SIMulator
PMOS	P-type/Positive Metal–Oxide–Semiconductor
RF	Radio Frequency
RFID	Radio-frequency identification
RMS	Root-Mean-Square
RU	Reader Unit
SU-8	Epoxy Structured by Uv
TSB	Telemetric Smart Bracket
v	velocity

I. INTRODUCTION

The success of orthodontic treatment is not limited to obtaining a correct occlusion. The risks inherent in the treatment must be known to be anticipated. The orthodontist has a duty to preserve the dental organ and the surrounding structures (Maire and Meyer, 2014), for this the tooth movement should normally be atraumatic, well-directed, and efficient. (Lapatki *et al.*, 2007)

The multi-bracket appliances that are on the market lack quantitative measurement to determine the exact force applied to the tooth, and do not offer the orthodontist this possibility of controlling the force in its direction and intensity during tooth displacement. Hence the need for an individual system on board each bracket to measure and calculate the forces applied by the orthodontic wire on the tooth in all directions.

The requirement of well-directed and adequately dimensioned forces and torques in all three dimensions inspired the design and the development of smart brackets since 2005 by a team from the Department of Orthodontics, School of Dental Medicine, University of Freiburg, Germany; in collaboration with the Department of Microsystems Engineering (IMTEK), University of Freiburg, Germany. A bracket capable of measuring all six force and torque components exerted from the archwire via the bracket to the tooth, thus providing objective feedback for the orthodontist. (Bartholomeyczik *et al.*, 2005)

This work pretends to be a narrative review of the scientific literature and its objective is to describe the smart bracket concept, the main stages of its evolution over the years. Also, to know where are we currently with the smart bracket? and what would be the obstacles encountered and the solutions to be provided for the next steps to finally reach its commercialization? The description of fixed orthodontic appliance, its iatrogenic effects linked to the inadequacy application of F/T, and some notions about optimal force were also touched on.

Materials and Methods:

For the elaboration of this bibliographic review, articles were searched in different academic databases and search engines (B-On, Scopus, IEEE Xplore, Springer, Elsevier

ScienceDirect, PUBMED, Academic Search Complete) and Mendeley for the management of bibliographic references.

It was also used several reference books in the area of Orthodontics and Biomechanics. (Contemporary orthodontics, Orthodontics – Current principles and techniques …)

The following keywords were used in different combinations according to Medical Subject Headings terminology: "Orthodontic Brackets"; "Torque"; "Root Resorption"; "Stress, Mechanical"; "Calibration"; "Wireless Technology" and "Radio Frequency Identification Device".

Most of the relevant articles were found in the Scopus database. Identified articles were assessed according to well-defined inclusion and exclusion criteria.

Regarding only the Smart bracket project, inclusion criteria were used to narrow the search: for search, academic databases in the bioengineering field were used; publication date. 2005-2020; languages: English, French, Portuguese, German; only full articles. The following exclusion criteria were used: articles without scientific rigor; articles with only abstract available; unavailable articles; out of research topic. 20 articles were selected and studied. Priority was given to articles published between 2011 and 2020 deemed very relevant, but also to those published before this period deemed interesting for understanding its evolution and history. In addition to introduce the means of measurements that existed before the smart bracket and for some that still exist. The final selection includes 31 articles and reviews included in the period 1990 until 2020 and 4 books.[1]

II. DEVELOPMENT

1. FIXED ORTHODONTIC APPLIANCES

Current Multi-bracket appliances (Fig.1) are commonly used in orthodontics to correct malocclusion and tooth malposition. They are the most efficient technique (Proffit and Fields, 2000).

[1] See appendices for more details.

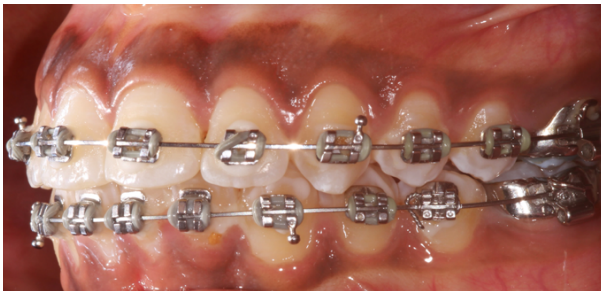

Figure 1 : Multi-bracket appliances, Straight-Wire technique[2]

1.1 Description of components

The component parts of a Multi-bracket appliance are: (Boileau, 2011)

- **Orthodontic brackets / Molar tube:** Brackets are adhesively bonded to the to the vestibular or lingual surface. In the vestibular, brackets are mostly available in metallic or ceramic material (aesthetic).

- **Molar bands:** attached to the teeth via cemented bands (most often at the molar level).

- **Archwires:** Fixed-appliance therapy has benefited greatly from the introduction and evolution of innovative materials such as super-elastic and shape-memory-archwires. As has been shown in (Fuck and Drescher, 2006), the use of even such advanced materials does not fully prevent the clinician from applying excessive forces and torques to the teeth.

  Inserted into the slot of the brackets, it performs various functions: (i) Move a tooth or a group of teeth e.g. Levelling and alignment (The characteristics of the arch such as the nature of the alloy, section of the arch ... and its deformation during insertion into the attachment are responsible for the force exerted on the tooth), (ii) Serve as a rail to guide the movement (e.g. canine recoil), and (iii) oppose movement in the anchoring areas. (Burstone, 2005)

- **Ligatures** (elastomeric, steel ties or self-ligating) which hold the archwire at the bottom of the slot of the brackets.

[2] Photo taken by BENSMAIL Y., Hospital Robert Debré-Paris (2014).

- **Auxiliaries** (power chain, active coil, intermaxillary elastics… which also deliver forces to the system)

1.2 Principle

- In the Multi-bracket appliances, the archwire transmit information to the uninformed brackets, e.g., Tweed technique and for the sake of simplification of handling, pre-informed brackets have been manufactured (e.g., Straight-Wire technique). There are many different pre-information depending on the technique. (Kerner *et al.*, 2011)

- The technique is said **segmented** (e.g., Ricketts bioprogressive, Burstone's) when several groups of teeth are individualized, and it is said **continuous** when all of the teeth of an arch are supported by the same archwire (e.g., Tweed-Merrifield technique, Straight-Wire technique …). In this case, the clinician encounters a more complicated and thus awkward scenario when forces and torques are exerted at multiple locations on the dental arch. As a consequence, unwanted side effects, e.g. tooth movements in the wrong direction or occlusal-plane canting, may easily develop. (Proffit, 2000; Burstone, 2005)

2. FORCES/TORQUES APPLIED TO THE TEETH

The applied force system induces differential mechanical tensions in the periodontal ligament of the tooth and consequently, enable movement of the tooth in a specific direction via stimulated remodelling of the alveolar bone (Reitan and Rygh, 1994). Moreover, unexpected and unwanted tooth movement can easily result when an important component of the applied force-torque system is overlooked (Proffit, 2000)

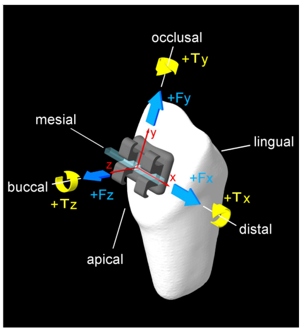

Figure 2 : Force and torque application to individual teeth using a multi-bracket-appliance. (adapted with permission from the author, Rues, 2011).

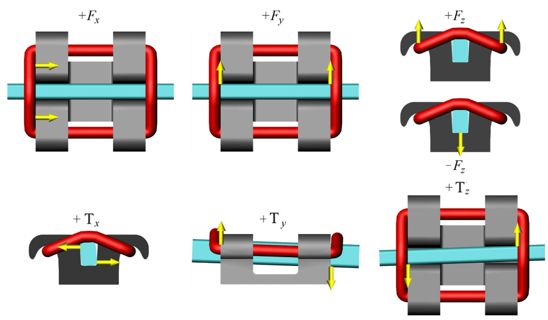

Figure 3 :Transfers of F/T components from an archwire to the brackets in clinical situations (adapted with permission from the author, Rues, 2011).[3]

2.1 Optimal force:

- **Definition:** It could provide the fastest speed of tooth movement without irreversible damage to the roots, alveolar bone and periodontal ligament. The optimal intensity of force should be the one that has the best yield in velocity of tooth displacement, ie the force is optimal when the ratio velocity/force (v/F) is maximum (Dorignac *et al.*, 2008). A physiological definition according to Profitts (*cit. in* Dorignac *et al.*, 2008) optimal force should be just sufficient to stimulate cellular activity without obliterating the blood vessels of the ligament.

A precondition for directed tooth movement is a 3-D controlled application of forces and torques over a period of time. Moreover, efficient and atraumatic orthodontic treatment requires the application of forces and torques in certain magnitudes and ranges, respectively. Optimal F/T according to Sergl (*cit. in* Bartholomeyczik *et al.*, 2006) depend on the kind and direction of tooth displacement and are typically between 0.1–2 N and 1– 50 N·mm**,** respectively. For Proffit, the forces and torques are in the range of 0.1-1.3 N and 2–15 N·mm**,** respectively, initiate efficient biological processes in the periodontal ligament and the alveolar bone (Proffit, 2007)

Some authors raised the question of the safety or otherwise of orthodontic appliances. There is, however, a consensus that the lower the force level, the less lesions there are, and the goal is to get as close as possible to the physiological displacement of the teeth. (Dorignac *et al.*, 2008).

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[3] **The x-axis** for mesio-distal direction.
The y-axis for apico-occlusal direction.
The z-axis for linguo-buccal direction.

Author	**Year**	**F [N]**
Storey et Smith	1952	1.5-2.5
Reitan	1960	0.4-1.4
Lee	1964	1.5-2
Hixon et al.	1969	1-3
Jarabak et Fizzel	1972	1.05-5.7
Quinn et Yoshikawa	1988	1-2
Sergl, H.-G.	1990	**0.1–2**
Lee	1995	2.55-2.73
Kuros et al.	1996	0.3-1
Owman-Moll et al.	1996	0.5-2
Uematsu et al.	1996	2.5
Proffit	2000	**0.1 – 1.3**
Iwaski et al.	2000	0.18-0.50
Lee	2004	1
Hoshino-Itho et al.	2005	2.5
Tuncer et al.	2005	0.9
Perinetti et al.	2005	2.5
Sugiyama et al.	2003	2.5
Batra et al.	2006	1

Table 1 : Value of orthodontic optimal force in humans according to the authors.

But it remains subjective, F/T must be measured. The need for a system capable of measuring forces and torques seemed necessary because suboptimal, i.e., too small forces and torques are ineffective or may prolong the duration of the treatment. Conversely, excessive forces and torques may lead to periodontal damage and considerable root resorption. (Darendeliler *et al.*, 2004; Becker *et al.*, 2017)

3. IATROGENIC EFFECTS LINKED TO THE INADEQUACY APPLICATION OF FORCES / TORQUES BY THE MULTI-BRACKET APPLIANCES

In orthodontics, the iatrogenic effects can affect both dental and surrounding tissues, hence the need to inform the patient of these possible risks before starting treatment and to individualize and optimize each treatment. These damages are correlated with the magnitudes of the load therapeutically exerted on the teeth. (Proffit, 2013)

3.1 Iatrogenic Effects On Dental Tissues

- **Root Resorptions**

Root resorption of permanent teeth corresponds to cemento-dentin lysis; it is pathological and irreversible. Resorptions may appear following the application of orthodontic force. They are inflammatory type and often external. They most often stop after the application of force has stopped. All orthodontic treatments on mature teeth cause a certain amount of resorption. This event, which affects the maxillary incisors more, is generally clinically insignificant. However, it can happen that resorptions exceed 1/3 of the root length, thus risking having a detrimental effect on the longevity of the teeth on the dental arch. (Samadet and Bacon, 2007)

Regular radiographic monitoring such as retro-alveolar radiographs, (at least the incisors) before treatment, then 6-9 months after the start of treatment, then every 9 months is recommended. When resorption appears, the patient must be informed and it is recommended to make an "orthodontic rest" of 2 to 3 months, maintaining the passive archwires. (Maire and Meyer, 2014)

By ruling out biological risk factors which have no relation to our subject and that are besides difficult to modify (systemic, anatomical, traumatic and functional...). There are mechanical risk factors:

- Applied force (intensity and rhythm) : heavy and continuous forces are the least favourable therefore those which create more root resorption (Samadet and Bacon, 2007; Dorignac *et al.*, 2008; Maire and Meyer, 2014). Thus light continuous forces are preferable to heavy forces for more physiologic dentofacial orthopaedics.(Utreja, 2018)

- Type of movement: ingression, the "Jiggling" movement, root straightening.

- Duration of treatment: the longer the treatment, the greater the risk

- Others: such as the placement of included teeth, orthognathic surgery.

- **Root bends (Dilaceration):** orthodontic displacement of immature teeth can cause the appearance of curved root.

- **Pulp involvement:** pulp reactions during orthodontic treatment are minimal. Cases of necrosis have been reported, but most often involve teeth that have suffered previous trauma. However, heavy and continuous orthodontic forces could cause this type of complication by abrupt movement of the apex, causing rupture of the neurovascular bundle.(Maire and Meyer, 2014)

3.2 Iatrogenic Effects On Periodontal Tissues

- **Mobility and dental pain :** there is a direct relationship between the intensity of the forces and that of dental mobility and that of pain. (Proffit, 2013)

- **Gingival recession:** orthodontics can favour the appearance of gingival recessions when the teeth are far from their bony support by the non-control of movements and forces among others (mandibular incisors most affected).

- **Alveolysis:** in the presence of weakened periodontium or unstabilized periodontitis, orthodontic treatment may create dehiscence and fenestration by moving the teeth away from their bone support. The orthodontist must be even more vigilant in ensuring anchorages, limiting forces and dental movements.

4. BASIC NOTIONS IN MICRO/NANO-ELECTRONICS (MNE)

Before describing the system, it is judicious to recall some basic physics definitions and/or principles on how applied forces can be measured by a sensor and transferred.

- **Stress**: is defined as the average force per unit area that some particle of a body exerts on an adjacent particle, across an imaginary surface that separates them. It can also be interpreted as the amount of internal resistance force of the deformed material.
- **Strain**: is a normalized measure of deformation representing the displacement between particles in the body relative to a reference length.
- **The piezoelectric effect** is the property of certain materials to become electrically polarized under the external action of mechanical stress and vice-versa. Some piezoelectric materials: Quartz, synthetic ceramics, Topaz...
- **The piezo-resistive effect** consists of the modification of the electrical resistivity of a material when it is subjected to external mechanical stress. Some piezo-resistive materials: germanium, polycrystal or amorphous silicon.
- **Piezo-resistive stress sensor** is a device that measures the mechanical stress. An external mechanical deformation (elongation or a shortening) causes a change in electrical resistance of the material and measuring that electrical resistance variation one can extract information about the amount of mechanical stress being applied. Silicon material is

generally used to make piezo-resistive stress sensor devices, same as used in the electronic circuits industry. The base of a piezo-resistive electronic chip is a crystalline silicon disc less than a millimetre thick, also called a silicon wafer. The use of these microelectronics materials allows good integration of the stress-strain sensors with the rest of electronic CMOS circuits.

- **CMOS**: Complementary metal–oxide–semiconductor, is a type of metal–oxide–semiconductor field-effect transistor (MOSFET) fabrication process used in current electronic circuits to process mathematical logic functions. CMOS technology is used for constructing integrated circuit (IC) chips and also used for analog circuits such as image sensors (CMOS sensors), data converters, RF circuits. (Gieschke *et al.*, 2009)
- **Piezo-resistive Stress Sensors in CMOS Technology**:

- Sensors for In-Plane Stress: Field effect transistor (FET) with four electric contacts, also called piezo-FET, are ideally suited for the detection of in-plane mechanical stress components in integrated chips with larger sensor arrays since they offer sufficient sensitivity, can be operated in a switched current mode for the reduction of non-mechanical contributions to the sensor signal and can be set to a high-impedance state using the electronic gate electrode. (Gieschke and Paul, 2010; Lemke, Baskaran and Paul, 2012)

- **Piezo-resistive sensors for out-of-plane shear stress** are realized in CMOS technology using silicon substrates (silicon wafer), by exploiting the shear piezo-resistive effect. A setup comprising a silicon bridge with SU-8 posts induce well defined and homogeneous vertical shear stress in the chip surface. (Baumann *et al.*, 2009; Lemke *et al.*, 2009, 2013)

5. BEFORE SMART BRACKETS

5.1 Measurement ex-vivo

– **Orthodontic SIMulator (OSIM) :** In-vitro measurement devices using macroscopic, cable-connected electric force sensors (Badawi *et al.*, 2009) . Although this device is fully functional, it is relatively bulky with a very high cost, thus is not practical to use in clinic making it unsuitable for broad application as an orthodontic research and didactic tool.(Becker *et al.*, 2017)

5.2 Measurement in-vivo

– **Spring balances:** For measuring tensile and compressive forces applied by rubber bands and springs, on only one direction, and with a lack of measurement precision.

– **3D measurement system :** only one apparatus (Rosarius *et al.*, 1996; Friedrich *et al.*, 1998) has been developed and described in the literature that permits the measurement of F/T exerted during fixed appliance therapy to be 3D monitored in-situ. The complex configuration of this measuring system (consisting of separable brackets and an extra-orally supported FMT) is responsible for several significant limitations hampering clinical application: (i) the long time needed for fixation and adjustment, (ii) the impossibility for force-torque measurements to be determined simultaneously at several teeth, (iii) the limited measurement accuracy associated with the limited rigidity of the sensor system itself and its support by the movable and resilient facial skin.(iv) measurement bias is relatively high, and the unknown amount of friction between the wire and bracket is often not taken into account.

– **Elastomeric tactile sensor**: In previous attempts to apply miniaturized sensors to orthodontic brackets a capacitive-type elastomeric tactile sensor to measure the force for the application of orthodontics, but only a single force component has been measured. (Tseng, Yang and Pan, 2004)

6. SMART BRACKETS CONCEPT

The principle of the smart bracket concept is the combination of an orthodontic bracket with an integrated microelectronic chip equipped with multiple piezoresistive stress sensors. In addition, the measurement information is transmitted wirelessly to the computer screen reader, that the orthodontist place near each tooth during an examination. In this way, an objective feedback is provided to the orthodontist.(Bartholomeyczik *et al.*, 2005)

- All six force and torque components exerted from the archwire establish mechanical stress distributions in bracket.

- By exploiting the piezo-resistive effect in silicon, stress in the plane of a sensor chip inside the bracket is measured by microsensors (Lapatki and Paul, 2007)

- Force and torques externally applied to the bracket are extracted and calculated from measured stress values. (Rues *et al.*, 2011)

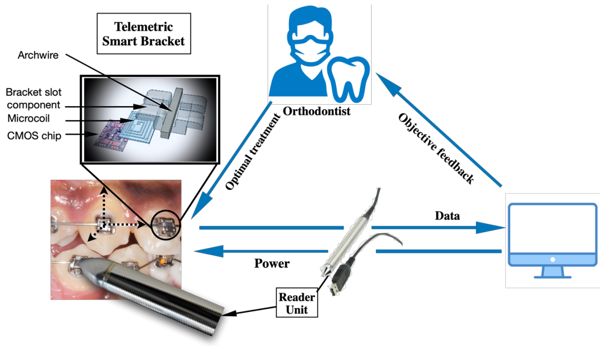

Figure 4 : Smart Bracket Concept[4]

7. TELEMETRIC SMART BRACKET

7.1. System Overview (2020 Version):

-The CMOS chip comprises 32 piezo-FET devices.

-The 32 sensors are consecutively connected to the readout unit by a 5-bit multiplexer (MUX).

- Variable-gain differential operational amplifier block, plus a 10-bit analog-to-digital converter (ADC) performs the sensor readout.

- Telemetric wireless interface working at 13.56 MHz with the sensor data being transmitted to an external unit at data rate of 27.1 kbit/s. (Kuhl *et al.*, 2013)

- For inductive coupling, a planar spiral-shaped microcoil based on copper electroplating on glass substrates has been developed.

- The assembly of chip and coil (Fig.5) has an area of 2×2.7 mm^2 connected via flip-chip bonding. It meets the given dimensional volume stress criteria of only 2×2.8×1 mm^3.

- The electrical interconnection to the CMOS chip was realized by stud-bump-assisted flip-chip bonding followed by an underfill with a biocompatible epoxy.

[4] The TSB system including a standard bracket slot component, a microcoil for telemetric operation via an inductive link, connected to and powering a CMOS sensor chip. RU : for Receiver/transmitter coil : Energy transmission into bracket, Data transmission to orthodontist (3D F/T).

- The circuit is implemented in the 0.35µm CMOS

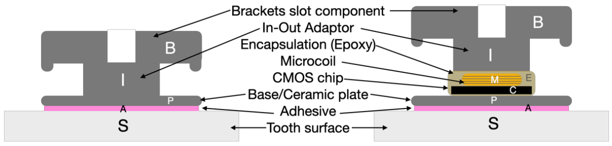

Figure 5 : Schematic cross-section of TSB assembly attached to a tooth and standard bracket.

7.2. System Components:

- Sensor Elements : The distribution of sensitive sensors on the chip surface is not done randomly, but according to FEA simulation. (Kuhl *et al.*, 2013; Becker, Lapatki and Paul, 2018). In all previous versions, there were two types of sensors for measuring two different stress components (M. Kuhl *et al.*, 2011; Handwerker *et al.*, 2012). The in-plane shear stress therefore is measured by an **NMOS** type sensor rotated by 45º with respect to, while the **PMOS** type is oriented parallel to the coordinate system and is sensitive to the difference of in-plane normal stresses. The CMOS chip in its 2020-year version, comprises 32 piezo-FET devices distributed on the surface of the chip and contains only **PMOS-FET** stress sensors primarily sensitive to the in-plane normal stress difference and has additional test pads along the shorter side which are used as contact pads for the wire-bonded microcoil.(Hafner *et al.*, 2020)

- External Unit and Wireless Interface: The power and data transfer were performed using a telemetric link based on inductive coupling at a carrier frequency of 13.56 MHz and a data rate of 27.1 kbit/s.

- **Microcoil:** For telemetric coupling, in the last prototype of year 2020, the novelty is the replacing the planar microcoil with a helical wire-bonded microcoil to extend the transmission distance. This planar spiral-shaped microcoil was realized by a planar wafer-level process based on copper electroplating on glass substrates. Using an automatic wire-bonder, the microcoil is wound around an SU-8 post attached to the CMOS sensor wafer without compromising his functionality. These microcoils with a diameter of 1.9 mm and a maximum height of 500 µm are fabricated in a multilayer winding process.
- **The Reader Unit :** The telemetrically extracted sensor data are demodulated, digitized and decoded by the reader unit, which is connected to a graphical user interface (Hafner *et al.*, 2017). A compact RU which maximizes the transferable power while simplifying the electronic equipment was designed. Consisting of a standard

microcontroller, a commercially available RFID chip and a reader antenna (an air coil with an inner diameter of 6 mm).

7.3. Calibration And Telemetry Result:

- 6DOF Force/Torque Measurements (Hafner, Lapatki and Paul, 2018; Hafner *et al.*, 2020)

Calibration	**Fx (mN)**	**Fy (mN)**	**Fz (mN)**	**Tx (N.mm)**	**Ty (N.mm)**	**Tz (N.mm)**
2018-year: 3500 random load cases	36	55	57	0.137	0.140	0.057
2020-year: 200 load cases	45	48	106	0.192	0.275	0.141

Table 2 : RMS deviations between extracted and applied values found in each F/T component from the in-vitro experiments carried out in 2018 & 2020 with a real smart bracket.

- Telemetry:

The targeted resonance frequency was 13.56 MHz in agreement with the ISM-band reserved for medical RFID systems. Microcoils with 23 turns showed resonance frequencies close to the expected value of 13.56 MHz with a resonance peak at 13.8 MHz.

- The transmission distance: The maximum distance coil-to-coil is 5 mm.

-The minimal transferred power to keep the system in operation is 17 mW. The system achieves a power consumption of 1.75 mW for the stress evaluation.

III. DISCUSSION

A system technique for complete dental monitoring of F/T applied to individual teeth offers attractive perspectives in several fields. In the near future, the "Smart bracket":

- May allow dental clinical research to define better orthodontic brackets, archwires, and develop gentler, and less painful methods of application through the objective feedback provided to the clinician.(Bartholomeyczik *et al.*, 2006)

- Could be highly useful tools for fundamental biomechanical research, e.g. in verifying biomechanical theories (Lapatki *et al.*, 2007), and objective F/T monitoring during experimental studies on tooth movement. This could considerably improve biomechanical research through large-scale experimental simulation of therapeutic situations.

- Could be highly useful tools for biological research to validate exactly the optimal force / torque interval for all types of biomechanical movement

- Could also prove to be a valuable feedback tool in the education and orthodontic training. In this manner, the experience that the clinician needs to move teeth efficiently and with fewer side-effects could be acquired interactively and with objective control. (Lapatki and Paul, 2007) Start commercialization of smart typodont i.e., typodont with smart brackets on all individual teeth, to be applied in fundamental research and orthodontic training seems a very good start.

- The most attractive perspective is related to the method's potential for clinical application. to individualize the treatments because each clinical case is a unique case, and we cannot simulate all the possible cases during the training of orthodontists. It also makes it possible to reduce the radiographic monitoring of the teeth for the risk of root resorption, and therefore to irradiate the patient less.

- However, in all the published studies on the 'Smart Bracket', the F/T measured by the chip during calibration came only from the archwire, it would be interesting to also measure the forces applied by the auxiliaries, such as elastic chain, or spring.

And what about the forces this time, interdental, not measured by the system? And which are the result of the complexity of the Multi-bracket appliances which assembles several teeth (Burstone, 2005) and acts like a person pushing wooden crates. In this case the stress must be measured from the enamel because the force does not apply to the bracket.

- Also, without battery and memory embedded in the bracket, it would be impossible to save the data in order to follow the F/T duration curve. This is important for the orthodontist to know exactly how often the intensity of force decreases between the two clinical appointments. This will guide the clinician to use one archwire rather than another or to substitute an auxiliary for another. (e.g., spring instead of the elastic chain, which in a humid and hot environment like the mouth, the elastomer loses a large part of its elastic properties). The work of Kutbee *et al.* (2017) are interesting on the use of biocompatible micro-battery in the mouth for therapeutic purposes.

- For clinical application relying on in-vivo measurements on patients, wireless measurement is mandatory, but telemetric data and energy transmission was shown at single-bracket level (Hafner *et al.*, 2020), it would be interesting to know if the transmission range is affected or not when several brackets are next to each other.

- The use of smart brackets in a sectoral manner, i.e., on a few teeth only proves a complicated task for the orthodontist if applicable, who should compensate with the composite or the bending of the archwire the difference in thickness that exists with conventional brackets. Also, this thickness of the smart bracket increased by the thickness of the chip, will it meet the aesthetic criteria of patients who are becoming more and more demanding?

- For the exclusively clinical part may not be a priority at the moment for researchers, has the bracket debonding phase, been thought out and anticipated ? because the goal would be to remove the bracket without breaking the chip and without any risk of removing the enamel with it, especially when it comes to a ceramic bracket.(Aknin and Molle, 2005)

IV. CONCLUSION

The development research project 'Smart Bracket' once concluded according to his initial main objectives and marketed will undoubtedly change orthodontic practice in the good direction, opening a new way of working, but above all a new chapter to be exploited still blank and little known in the field of orthodontics.

But for now, some pieces of the puzzle are still missing, to hope to have the final prototype in the coming years, researchers must overcome the obstacles encountered and face the real challenge which consists of combining multiple functions in a single miniature chip, a function of precise measuring F/T components from archwire and auxiliaries applied to brackets, a telemetry reserved for the medical sector sufficient enough to transmit the data, and all in an orthodontic bracket that meets the requirements aesthetics of patients.

Will the 'Smart Bracket' see the "light of day" for a clinical application or rather have a biomechanical, biological research role, and/or an educational tool in orthodontic training? The future will tell us … But for my part, I will remain very optimistic about its achievement through access to information and to this world fully connected. Ideas can come from other fields!

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VI. APPENDICES

1. Inclusion & Exclusion:

Number of selected articles by chapter	Inclusion and exclusion criteria	References
Fixed orthodontic appliances & F/T applied to the teeth (3)	- Elsevier ScienceDirect, PUBMED - English, French - 2000 – 2020 - Most relevant articles were selected	(Fuck and Drescher, 2006; Dorignac *et al.*, 2008; Kerner *et al.*, 2011)
Iatrogenic effects (4)	- Elsevier ScienceDirect, PUBMED - English, French - 2000 – 2020 - Most relevant articles were selected	(Sauveur and Mesbah, 2003; Samadet and Bacon, 2007; Elhaddaoui *et al.*, 2016; Utreja, 2018)
Before Smart bracket (4)	- English, French, German - 1990 – 2020 - Scopus, PUBMED.	1996 : (Rosarius *et al.*, 1996) 1998 : (Friedrich *et al.*, 1998) 2004 : (Tseng, Yang and Pan, 2004) 2009 : (Badawi *et al.*, 2009)
Basic notions in MNE & Articles related to smart bracket project of IMTEK (27)	- English, French, German, Portuguese - 2005 – 2020 - B-On, Scopus, IEEE Xplore, Springer, Elsevier ScienceDirect, Academic Search Complete - Only articles that discuss the smart bracket project were selected. - Full articles	2005 : **3** (J. Bartholomeyczik, Doelle, *et al.*, 2005; J. Bartholomeyczik, Haefner, *et al.*, 2005; Julian Bartholomeyczik *et al.*, 2005) 2006 : **1** (Bartholomeyczik *et al.*, 2006) 2007 : **4** (Gieschke *et al.*, 2007; Lapatki and Paul, 2007; Lapatki *et al.*, 2007; Suster *et al.*, 2007) 2009 : **3** (Baumann *et al.*, 2009; Gieschke *et al.*, 2009; Lemke *et al.*, 2009) 2010 : **1** (Gieschke and Paul, 2010) 2011 : **3** (M. Kuhl *et al.*, 2011; Matthias Kuhl *et al.*, 2011; Rues *et al.*, 2011) 2012 : **3** (Handwerker *et al.*, 2012; Lemke, Baskaran and Paul, 2012; Paul, 2012) 2013 : **2** (Kuhl *et al.*, 2013; Lemke *et al.*, 2013) 2017 : **3** (Becker and Paul, 2017; Becker *et al.*, 2017; Hafner *et al.*, 2017) 2018 : **2** (Becker, Lapatki and Paul, 2018; Hafner, Lapatki and Paul, 2018) 2019 : **1** (Berger *et al.*, 2019) 2020 :**1** (Hafner *et al.*, 2020)
Articles related to measurement of orthodontic force in other ongoing studies (4)	- English, French - 2005 – 2020 - Scopus, IEEE Xplore - These articles interested me in my research.	(Lin *et al.*, 2011; Fercec *et al.*, 2012; Shi *et al.*, 2012; Kutbee *et al.*, 2017)

Tab 1 : Inclusion & Exclusion criteria

2. Optimal force

Type of displacement	Force [gf]
Version	50-75 gf
Translation	100-150 gf
Root straightening (torque)	75-125 gf
Rotation	50-75 gf
Egression	50-75 gf
Ingression	15-25 gf

Tab 2 : Estimation of the forces to be used according to the type of displacement desired, adapted from (Dorignac et al., 2008).[5]

This table highlights two concepts:

• On the one hand, the notion of light force since no force exerted is greater than 150 gf = 1.47 N

• On the other hand it shows that the optimal force to be developed varies according to the mechanical tension surface following the different types of movements.

It is therefore the concept of mechanical tension that prevails in the biomechanics of dental displacement.

Ensures optimal rate of movement : Optimal mechanical tension → Maximal tooth velocity

3. Evolution of smart bracket

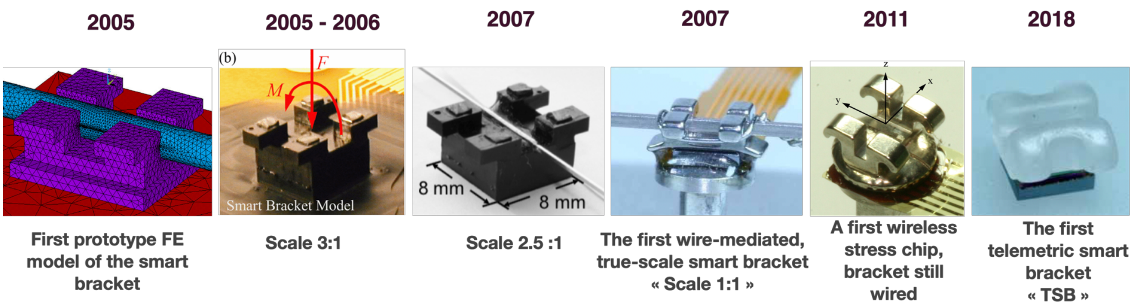


Fig. 1 : Evolution of smart bracket

[5] The gram-force (gf) is a metric unit of force, and is equal to a mass of one gram multiplied by the standard acceleration due to gravity on Earth, that is 1 gf = 0.0098067 N

4. Evolution of chip

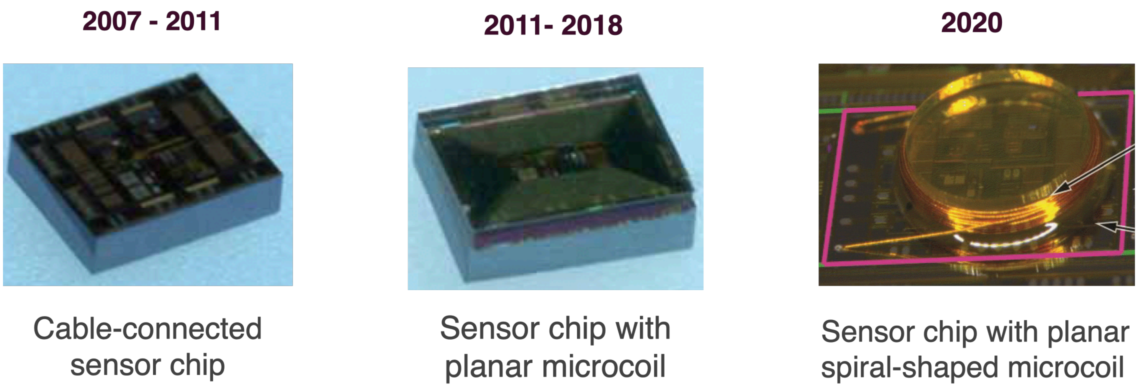


Fig. 2 : Evolution of chip (macrograph)

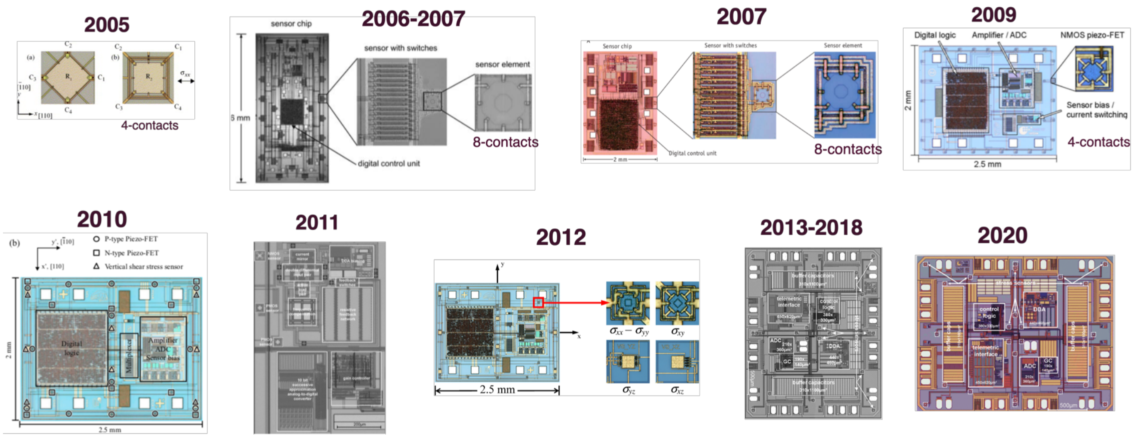


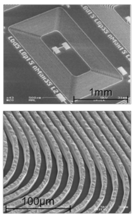
Fig. 3 : Evolution of stress sensor chip (micrograph)

Year \ Chip Characteristic	Number of stress sensors	Sensor type
2005	3	CMOS piezoresistive stress sensors with 4 contacts
2006	32	CMOS piezoresistive stress sensors with 8 contacts
2007	32	CMOS piezoresistive stress sensors with 8 contacts
2007	10	CMOS piezoresistive stress sensors with 8 contacts
2009	32	Piezo- FET : 32 NMOS / 32 PMOS
2010	32	Piezo- FET : 14 p-type, 10 n-type, and 8 vertical shear stress sensor (σzz r)
2011	24	Piezo- FET : 10 NMOS and 14 PMOS
2012	32	Piezo- FET :16 NMOS and 16 PMOS
2013-2018	24	Piezo- FET :10 NMOS 14 PMOS
2020	32	Piezo- FET : 32 PMOS

Tab 3 : Characteristic of chips by year

5. Telemetric operation / Evolution of Microcoil (micrograph)

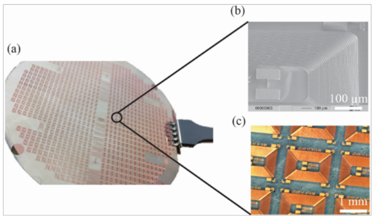
2011 / 2013



Planar gold microcoil

- 2x2.5 mm2
- comprises 35-winding microcoil with gold leads
- fabricated using Au electroplating in a thick photoresist mask.

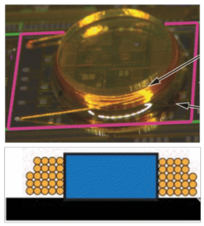
2017 / 2018



Planar Copper Microcoils

- 2 × 2.5 mm2
- comprises 35 windings and is 22 µm in height.
- fabricated using Cu electroplating into a photoresist matrix on a metallic seed layer

2020



Planar spiral-shaped microcoil

- A height of 125 µm (5 layers) and a diameter of 1.9 mm
- Realized by a planar wafer-level process based on copper electroplating on glass substrates

VII. ANNEXES

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