A wearable passive force sensor powered by an active interrogator intended for intra-splint use for the detection and recording of bruxism

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***Abstract*— A wearable bite force sensing system prototype made up of a passive force sensor and an active interrogator/reader is described. The system is aimed at bite sensing using a wireless link between the passive sensor to be located in the mouth and the external interrogator that can record the evolution of detected force. The interrogator generates a magnetic field that energizes the passive sensor which is also used as the information transmission carrier. The passive force sensor does not need a battery to operate it because it can extract the energy it needs to operate from the carrier field generated by the interrogator. Occlusal force quantification can be used for the detection of bruxing episodes and registration. The small size of the components used (smd) and its further size reduction if they are integrated would allow an implant the size of a tooth.**

Keywords-component; wireless sensor, passive force sensor, near field communication-based sensor.

I. INTRODUCTION

Bruxism is a pathology that causes involuntary bite and grinding that eventually results in dental damage and temporomandibular pain [1]. It appears to affect to over a 20% of the adult population to a varying degree. Most diagnoses are made based on the observed damage to the denture, when damage is already produced, and its treatment is mostly based in the use of dental splints to avoid further dental damage. The main limitation of the diagnosis of the pathology is the quantitative temporal evaluation of the force and its registration. If a prolonged recording were available, it would enable both the study of the pattern of the episodes and its evolution. This quantification in ambulatory situations remains an open area of research because the main limitation to a permanent recording method is the need for wires that connect the force sensors located within the mouth with the electronic recording equipment located outside. A permanently wearable sensing system that allowed quantitative evaluation and recording is highly desirable to be able to make a diagnosis based on quantitative data.

There have been some experimental studies of bruxism using piezoelectric sensors [2], force sensors [3] or electromyography [4], but these studies have always been carried out in an environmentally controlled experiment because they used wires to transmit the information recorded by the sensors. The use a of Bluetooth-based wireless communication system between a mouth located sensor and an external receiver has been developed for diagnosis and registration of bruxing episodes by the authors in [5]. However some problems related with the size of the intrabucal device, with the short lifetime of the small (intrabucal) battery and with biological tissue absorption, have limited its applicability. The main results of these studies related to bruxism episodes can be summarised in Fig. 1, which represents the distribution of the bruxist population considering the bite force and the aggregated duration of the episodes as the most important factors of bruxism episodes. It is important to point out that everybody subconsciously clenches their teeth at sometime during the day and this could be considered as bruxist activity, but the term bruxism is only used though when the duration and intensity of this activity has a bearing on dental wear and the appearance of temporomandibular joint (TMJ) problems.

In this work we propose a system that uses a wireless link between a passive force sensor to be located within a splint in the mouth cavity and an external active unit that energises the sensor and permanently records the force measurements and we report the development of a prototype. This system would permit permanent occlusal force measurement. The prototype uses a Near Field Communication (NFC) scheme similar to that used in low frequency RFID technology. The reader generates a low frequency magnetic field that is used as the information carrier and to power the sensor. The low frequency magnetic field is not absorbed by the biological tissue as are other RF signals, although the communication range is limited to a few cm's for reasonable amplitude values of the excitation. The prototype is intended to evaluate the viability of the approach, but some further development (water isolation, robustness,…) and integration to further reduce its size are still necessary before it is implanted into a deployable splint. A final device may be the size of a tooth or smaller.

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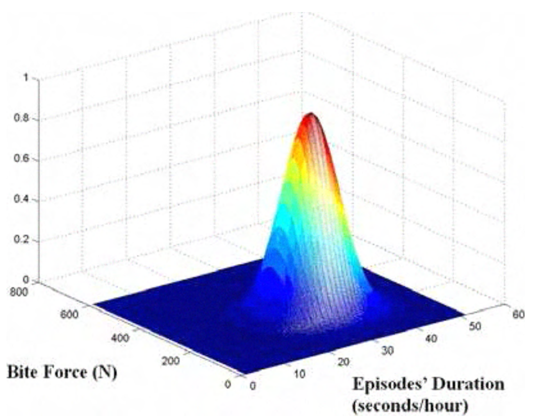

Figure 1. Distribution of bite force and aggregated episode duration per hour for bruxist population in (%).

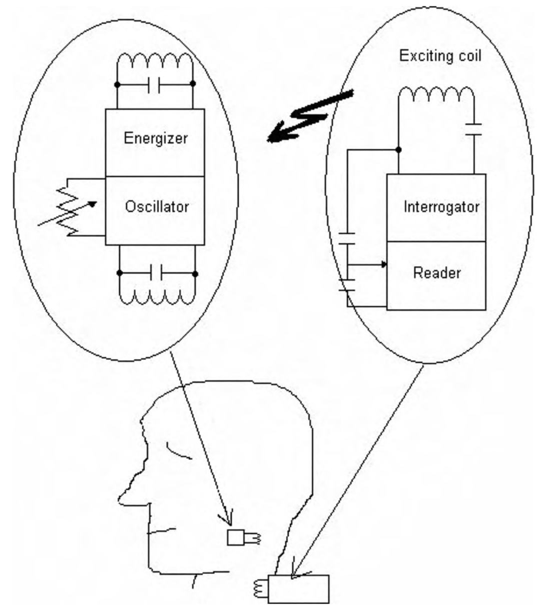

Figure 2. Scheme of the proposed system.

II. System Description

The system uses a communication technology based on Radio Frequency Identification (RFID). A low frequency (125 kHz) magnetic carrier field was chosen because it has good penetration capability -not absorbed by the biological tissue-, the inductive coupling of the carrier field allows the energizing of the passive parts and the size of the transmitting coils and other components to be reasonably small. This magnetic field is commonly used in passive RFID readers in shops so that biological damage should not be different. RF communication suffers from higher absorption at the biological tissue, does not allow the sensor to be energized, which would require the use of a battery, and the components size, which depends on the operation frequency being larger. Like RFID, the basic system is made up of an interrogator and a passive sensor. The term passive indicates that it does not use a battery. The interrogator (reader) is usually made up of a microcontroller-based unit and an analogue front-end. The analogue front-end unit generates a low frequency (125 kHz) magnetic field that induces a voltage at a tuned LC circuit in the supply subsystem of the sensor. This voltage is rectified and used to energize the rest of the sensor. This tuned LC circuit is not the same LC circuit that is used to communicate to the reader because energy must be permanently supplied to the sensor to operate and the communication tank is tuned and detuned. The small variation produced in the field by the modulation does not affect the energizing part of the sensor. The sensor is only powered when there is enough induced voltage at the coil, which implies a maximum distance to the reader.

When the sensor is energized, it starts a low power oscillator whose oscillation frequency is directly related to the resistance value of a force-resistance transducer. A force dependent oscillator operation was chosen because it permits continuous monitoring if the interrogator is active, and it draws less power in continuous operation than a micro-controlled-based unit that samples, converts and digitizes the readings. In order to transfer the data to the reader, the output of the oscillator is used to bypass a capacitor of an LC tank tuned at the frequency of the interrogating field so that the oscillator tunes and de-tunes the LC circuit at the force dependent oscillating frequency, producing what is termed as backscattering or load modulation. This modulation is sensed at the interrogator as a slight amplitude modulation (typ. -60 dB), which is detected using an envelope detector and a locking amplifier. In this manner, the frequency of the detected signal is the frequency of the oscillating sensor, which depends on the applied force. Frequency modulation instead of amplitude modulation was chosen to make the system less sensitive to relative head movements which imply distance variation and correspondingly, undesired amplitude modulation; frequency is not affected if the sensor is within the communication range. The oscillator frequency range for the expected transducer values must be selected to match the frequency response of the reader. The demodulated frequency signal is used to evaluate the bite force sensed. Fig. 2 schematizes the proposed system. The sensor is presumed to be inside the splint located in the mouth.

III. Implementation

A. *The passive force sensor*

The passive sensor, which is the component to be eventually integrated in the splint, is made up of two different subsystems:

(I) A powering subsystem that is made up of (1) a tuned LC circuit, (2) a Schottky diode rectifier and (3) a low power low dropout regulator [MC78LC30] that provide a constant dc voltage with two capacitors at its input and output. The values of the LC circuit are chosen so that it resonates near 125 kHz. Ideally:

$$\sqrt{LC} = 2\pi \cdot f_0 = 2\pi \cdot 125kHz \qquad (1)$$

Subsystem (I) energizes subsystem (II) when there is enough interrogation field intensity.

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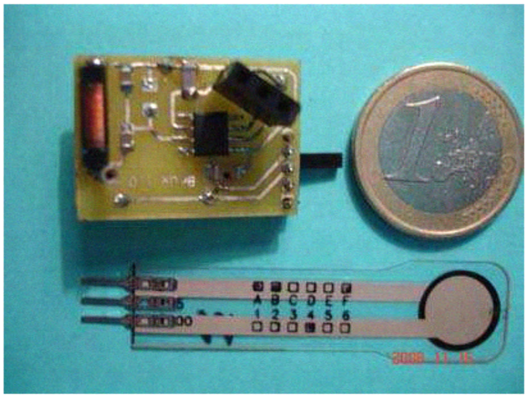

Figure 3. Picture of the passive sensor prototype and the transducer.

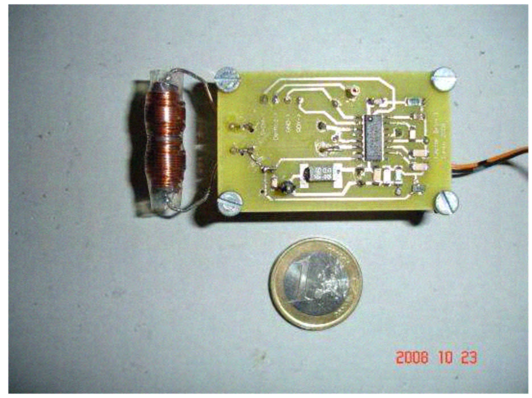

Figure 4. Picture of the interrogator/reader prototype.

(II) A force sensitive oscillator, which is made up of a low power relaxation oscillator [LMC555] and a few passive components, including a force to resistance transducer [ZFLEXA201-100] [6] which is 0.2 mm thick and has a sensing area of about 0.78 cm^2. This transducer is the element to be eventually located in the splint and it converts the occlusal force into resistance, which sets the oscillation frequency. The output of the relaxation oscillator drives a second LC tuned circuit, which is tuned and de-tuned at the oscillation frequency. The sensor oscillation frequency range of this component is chosen to match the response of the filter located at the reader element, and the maximum oscillation frequency is selected at the minimum resistance of the force transducer which presumably happens when a bruxism episode is occurring. When it is operating, this component consumes a power of about 250 µW. Fig. 3 shows a picture of the passive sensor prototype used to evaluate the system.

B. *The interrogator/Reader*

A reader is typically made up of a microcontroller and an analog front-end unit. This unit generates the field that energizes the passive sensor and detects the modulated signal that is produced at the excitation coil by the tuning and de-tuning of the sensor tank circuit. In our first implementation, we have only used the front-end unit that once it is powered it permanently generates the magnetic field using a series LC circuit. The microcontroller permits the control of the excitation activity duty cycle of the front-end unit and the reading of the demodulated signal. The demodulated output provided by the front-end unit was monitored using an oscilloscope in our case. In the built prototype, we have used an EM4095 analog front-end with external passive components. These components are selected to generate a 60 V_{pp} at the coil. An antenna current of 230 mA_{rms} corresponds to this value, which is below the 300 mA_{rms} limit rated in the specs [7]. A supply current of 175 mA was measured under the operating conditions for a voltage of 5V. This value results in a power dissipation of 875 mW, which corresponds to about 200 mW to the chip and 700 mW to the external current limiting resistor located in the excitation tank. The chip temperature increase is about 15 ºC, which is below the specified maximum temperature value (100ºC) if it operates at common room temperatures. A set of four standard rechargeable AA batteries lasts about 12 hours if the unit is permanently in the 'on' state. The values of some components of this circuit determine the filtering behavior of the demodulator. The components were selected to maximum sensitivity at a frequency of nearly 2 kHz which corresponds to the force threshold applied to the transducer during the grinding episodes. Fig. 4 shows a picture of the interrogator/reader prototype used to evaluate the system.

IV. RESULTS

The prototype sensor behavior was characterized using a compressive load test in the range of 0 kg - 60 kg [0 N – 588 N]. The force measurement range was selected because the occlusal force during a bruxism episode is expected to be around 100 kg, in accordance to the values which has been measured during episodes in controlled environments. The final value will depend on the specific person. Nevertheless, the results limit the force to about 60 kg to comply with the transducer specifications; considering that final prototypes will be embedded into a rigid splint, which will protect the sensing device, we estimate that the proposed transducer will withstand typical bruxism episodes. The load cell used for the measurements was a Vetek [8] model VZ266AH which operates up to 200 kg of compressive load. The transducer of the sensor was located on the load cell between two metallic pieces and the force was applied using a jack while the sensor was activated by the interrogator. The output demodulated signal provided by the reader was measured using the screen trace of an Agilent Infiniium 54832D oscilloscope. Fig. 5 shows the output frequency of the reader signal vs. the force applied to the transducer makes up part of the sensor as the force is increased and decreased; uniform distribution of force on the transducer area is not ensured. The data correspond to the results obtained with a transducer going from zero force to 50 kg and back within close reading distance. A similar behavior was observed using another transducer. A certain hysteresis was observed because the sensor is encapsulated in a plastic material and has some transitory response due to visco-elastic deformation and it takes some time for the final resistance value to be reached. It was also noted that the resistance of the selected force transducer depends on the distribution of force over its area (0.78 cm^2); during the test the

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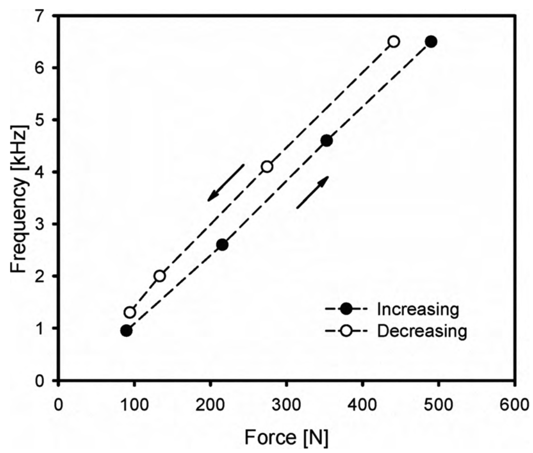

Figure 5. Measured demodulated output frequency vs. applied force [N] at the transducer.

the force was applied uniformly. If the force is applied at a limited area of the transducer, a different response is observed because a different value of resistance is obtained at the transducer for the same force. Eventually, the sensor must be calibrated once installed in a splint and the transducer must accommodate some mechanical adapter to obtain a uniform distribution of the applied force over the sensing area. Hence the response shown in Fig. 5 must be used only as a rough estimation of the response because a calibration depends on the force distribution over the sensing area.

The observed communication range is about 5cms, if the sensor is energized using a constant power supply (i.e., using an external supply or battery). However the range is limited to about 2.5 cm if the sensor is operated using only the magnetic field because up to that range a constant 3V is obtained from the regulator that energizes the oscillator. If the coils are separated more than a given distance, a lower voltage is obtained from the regulator and it affects the frequency of the oscillator; a lower voltage regulator could extend the range. This means that a calibration must assume a constant supply voltage and the sensor should be operated within this range to avoid the cross effect of voltage drop on frequency due to distance variation. Then, it is the regulator which sets the range limit for a given calibration. The magnetic induction along the axis of the coil (far field) can be evaluated as:

$$|B| \cong \frac{\mu_r \cdot \mu_0 N \cdot I \cdot r^2}{2} \cdot \frac{1}{d^3} \qquad (2)$$

where μ_r is relative magnetic permeability, μ_0 is the magnetic permeability, I is the current (excitation), N is the number of turns of the coil, r is the radius of the coil and d is the distance to the center of the coil along the axis. The necessary increase in excitation current to obtain a given field intensity as the distance is increased is not linear because the magnetic field decreases following the third power of the distance. Longer ranges could also be achieved using higher excitation current, but an external driver that can handle these currents is necessary and higher energy consumption results. Range is also heavily dependent on the tuning alignment of the LC circuits located at both the sensor and the reader. The tuning alignment of the tank circuits at the prototype was not optimized in this work. Nevertheless, the limited communication range can be considered an advantage because it avoids interference with other devices. Tests in patients are pending on sensor size reduction (under way) and its official approval.

V. Conclusions

A system made up of an active interrogator/reader and a passive sensor that can be used to record bruxism is proposed and a prototype evaluated. The system operates using low frequency magnetic field to energize a passive sensor to be located within a splint and also to carry the information on the force magnitude detected, in a communication mode of operation similar to RFID technology. The passive sensor extracts the energy it needs to operate from the exciting field and converts the sensed force into a frequency signal that is sent wirelessly to the reader using load modulation. A prototype of the passive sensor/active reader has been built to evaluate and characterize the behavior of the sensing system. The results indicate that the sensor can be used to monitor force as a function of time in a continuous mode, although it can also be enabled and disabled periodically by a controller. If it is integrated to further reduce its size and adapted to a splint, it can be used to detect and monitor bruxism using a quantitative method without the use of wires to communicate the data. In this way, bruxism patterns could be studied using real time data and used as a diagnosis tool. Size reduction of the intrabucal device allows not only a more comfortable diagnosis system for the patients, but it also benefits the quality of the results obtained, due to a minor deviation on the position of the temporomandibular joint from the relaxed state. Finally, it should be emphasised that the possibility of obtaining a device based on the ideas proposed would enable intrabucal pressure to be quantitatively assessed and bruxist behaviour to be diagnosed at an early stage, so that corrective actions could be programmed before the appearance of irreversible dental wear.

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