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TeethVib: Monitoring Teeth Functional Occlusion Through Retainer Vibration Sensing

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***Abstract*—This paper presents *TeethVib*, a retainer-formed wearable system that monitors teeth occlusion conditions via vibration signals induced by teeth contact. Occlusal diseases (e.g., tooth attrition, erosion, hypersensitivity, fracture, gum recession, TMJ pain) are common problems, especially when one has a combination of natural and false teeth. They pose great threats to oral health. *TeethVib* leverages teeth contact-induced vibrations to monitor and profile teeth' occlusion conditions. To acquire teeth contact-induced vibrations, *TeethVib* utilizes piezo sensing elements between two thin layered retainers. Then the captured vibration signals are used to infer spatiotemporal characteristics of this contact. We conduct real-world experiments over multiple articulator-based teeth models built with bite registration to validate our system design. The preliminary results show that it is feasible to profile teeth functional occlusion with *TeethVib*.**

***Index Terms*—Teeth functional occlusion, occlusal diseases, smart retainer, in-mouth monitoring, vibration-based inference.**

I. Introduction

Oral health directly impacts the overall health and life quality of an individual [1]. One of the important factors that affect oral health is teeth activity and functional occlusion conditions. Functional occlusion condition represents the contact quality between maxillary (upper) and mandibular (lower) teeth during chewing or at rest. When an individual has a combination of natural and false teeth, it can often lead to occlusal diseases [2]. Occlusal diseases could further lead to various consequences such as Temporomandibular Joint (TMJ) disorder [3]–[5]. The current dental practice utilizes the flimsy foil with ink (articulating paper) to conduct the bite check by asking the patient to tap on the foil [6]. However, this approach cannot capture the teeth occlusion condition when the patients are in their regular posture, i.e., daily teeth usage. Prior works on smart mouth guards have explored athletic usage (e.g., detecting impacts and concussion) as well as chemical-based sensing by embedding sensors in the mouth guards [7]–[10]. However, these prior works do not address the problem for long-term fine-grained occlusion condition monitoring.

We propose, *TeethVib*, a retainer-formed wearable system that captures the teeth contact-induced vibration to infer the occlusion condition and assist the occlusal diseases diagnose. The intuition is that when the surfaces of the upper and lower teeth touch, e.g., biting, grinding, this contact movement induces the retainer structure to vibrate. These impulsive signals can be captured by a retainer-formed structure with embedded piezo sensing element. Our system extracts features from these signals to further infer fine-grained teeth occlusion conditions. We conduct controlled real-world experiments with articulators and teeth models built from patients' bite registration to validate our system design. The contributions of this work are as follows.

- We present a new sensing form factor to measure teeth occlusion conditions.
- We design hardware and software to extract teeth contact-induced vibration and infer functional occlusion conditions from the acquired signals.
- We conduct real-world experiments with dental teeth models to validate our new form factor sensor designs.

II. Background

A. Teeth Occlusion

Teeth occlusion (tooth contact) are important metrics for dental practice [11]. 'Balanced occlusion' was described as one of the first concepts on optimum functional occlusion primarily for removable complete dentures [12]. As more natural teeth were restored with fixed prosthodontics, the concept of unilateral eccentric contact was subsequently developed for the natural dentition [13]. More recently, the concept of dynamic individual occlusion has emerged centering around the health and function of the masticatory system and not on specific occlusion [14].

Centric relation [15] is considered as the position of the mandible when the condyles are orthopedically stable. When the mandible closes in centric relation, it may create an unstable occlusal contact. An unstable occlusion will lead to elevated muscular activity to maintain the position of the mandible in a stable occlusion, which potentially leads to exceeding neuromuscular activity that damages the masticatory system [16]. As a result, teeth occlusion is critical to the health of the masticatory system.

B. Dental Articulator

Articulators are important dental tools for teeth occlusion condition analysis [17]. They are designed to provide different levels of restriction of joints as well as shown changing understanding of jaw movements [18]. For example, James Cameron's articulator focuses on the vertical translation of the lower member and adjustments parallel to the plane of a

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model's bite [18]. Later models, such as Bonwill's theory of occlusion-teeth, move to adjust for how the lower and upper members are in relation to a joint with either fixed or limited adjustment with absolute measurements [18]. In this paper, we utilize modern articulators based on a range of positions of the lower and upper members found to work on most patients today. Rather than using absolute measurements, dentists use imprints called registers to qualitatively determine the best position of the upper and lower members.

III. Related Work

A. On-head and In-mouth Sensing

Wearable sensors have been developed to monitor multiple head-based signals such as brain signal (EEG), muscle signal (EMG), eye signal (EOG), heart-rate variability (HRV), GSR (galvanic skin response), blood pressure. Head-based signals have tremendous value in inferring the user's health, mental, physiological, and physical states. Monitoring these signals using sensors around the head is more reliable compared to other form-factor since the sensors are close to the signal sources. For example, sensors placed around or inside the ears are proven to capture reliable physiological signals [19], blood pressure [20], eating habit [21], etc.

Besides on-head skin sensors, multiple sensing systems have also been designed to capture in-mouth signals for oral health monitoring. In particular, oral health has been used as an indication for the quality of life for a variety of population groups, including children, aging populations, and adults [22], [23]. The overall oral health-related issues are independent but correlated with reported physical, social, and psychological functioning [24]. Hence, systems have been developed to monitor oral health including saliva monitoring [25], teeth monitoring [26], eating habit monitoring [27]. However, none of the existed solutions focus on the form factor for teeth functional occlusion monitoring.

B. Body Vibration Sensing

The human body induces vibration that propagates through bones and muscles. Various sensing systems are developed to capture these body-induced vibration signals for different types of physiology information inference. Mokaya et. al. use accelerometers contacting skin surface to capture muscular vibration during people's workout to infer the level of fatigue [28]. Jia et. al. use geophone sensors placed on the bed frame to acquire heartbeat-induced vibration [29]. Khanna et. al. use accelerometers on the jaw to detect unvoiced speech via vibration induced by cheek muscle motion [30]. These prior works on body vibration sensing demonstrate the feasibility of indirectly infer physiology information from the signal. However, to the best of our knowledge, there is no prior work has been done on teeth vibration sensors for long-term fine-grained teeth activity monitoring.

IV. System Design

To capture vibration induced by teeth contacting and infer spatiotemporal information on the teeth functional occlusion,

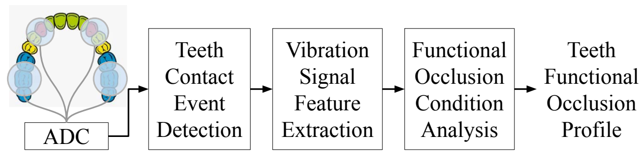

Fig. 1. *TeethVib* system overview.

TeethVib utilizes four modules as shown in Figure 1. The mouth-guard formed vibration sensor first captures the vibration induced by biting and other teeth activities. *TeethVib* then extracts the bite event through an anomaly detection-based algorithm. Next, *TeethVib* further extracts features from the detected event signal segment. Finally, a classifier is applied to the features to determine the functional occlusion conditions.

A. Turning Retainers into Vibration Sensors

To capture spatial and temporal characteristics of a bite and infer teeth functional occlusion, we place piezo sensing element (Section IV-B) at four areas of the retainer where molars and canines are located. To ensure a stable measuring point and prevent the teeth activities to wore the piezo sensing element, we build the retainer as a sensor by placing the piezo sensing element between two 0.6mm customized retainers. Figure 2 shows the procedure of how the retainer-formed sensor is built. Figure 2 (a) depicts the dental vacuum molding machine molding the retainer with thermal-forming material for invisible retainers. A second layer retainer is molded on top of the first layer. Then the retainer is separated from each other and the model as shown in Figure 2 (b). The piezo-based vibration sensor is then installed between the two layers of the retainers as shown in Figure 2 (c) and connected to the data acquisition platform with Analog-to-Digital converter as shown in Figure 2 (d).

Each piezo sensing element is approximately $1cm \times 1cm$ and placed between the two layers of the retainers. The natural structure of the teeth (grooves and cusps) makes the piezo sensing element stably located in between. However, for each person, the teeth structure varies. To ensure the effective contact and sensitivity of the sensor, the stranded wires are attached to each side of the film with strands evenly distributed over the film, and more details are explained in Section IV-B.

B. Piezo Sensing Element Fabrication

We now present a method of fabricating a low-cost, scalable, thin piezo sensing array, which can be augmented in cost-off-the-shelf retainers. Each piezo sensing element includes five main layers where piezoelectric film [31] are sandwiched by two micro-size copper wires and two thin thermal non-conductive tape [32] as illustrated in Figure 3. When the user grinds the teeth, the pressure placed on two sides of the piezo films will be transmitted to the monitoring circuit throughout the copper wires.

Among three main types of pressure sensors, including resistive resistor sensor, capacitive sensor, and piezoelectric sensor, the last type is selected due to its sensitivity, scalability,

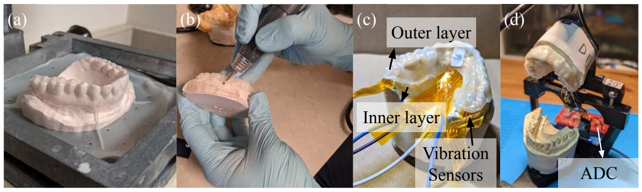

Fig. 2. *TeethVib* retainer-formed sensor building procedure.

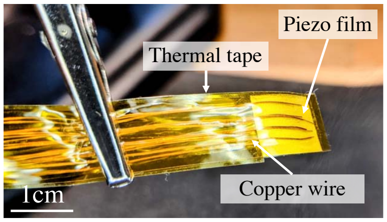

Fig. 3. One piezo sensing element.

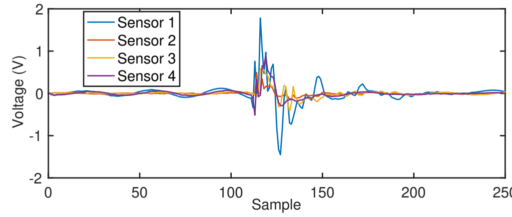

Fig. 4. Example signals of teeth contact-induced vibration.

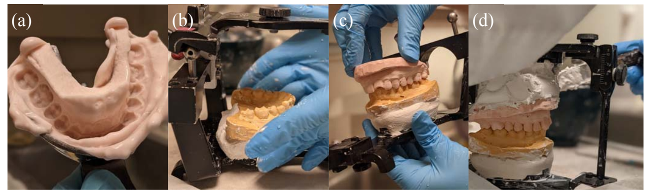

Fig. 5. Teeth model making procedure.

durability, and cost effectiveness [33]. Piezoelectricity is a phenomenon that allows materials to convert deformation into electricity and vice versa [34]. Peizolectric materials are often used for force/pressure sensors, transducers, and generators [35], [36]. The materials can be fabricated into nano- and microstructures and interfaced with soft tissues to monitor biological forces [37]. Piezo film is available in different thicknesses. Thinner films (28 and 52μm) are the most common. We select 52μm ones due to their mechanical qualities and robustness. Metalization options include a compliant silver ink and sputtered metalization (Cu-Ni). Silver ink is the best to handle mechanical stress created by teeth binding activities. The entire sensor has a thickness of 125μm. The sensor records teeth contact force ranging from 30 mN/mm^2 to above 250 N/mm^2 (with quantization of about 150 levels and a peak hysteresis of about 75%). A normal bite generates 0.4619 N/mm^2 pressure on average. The sandwiched fabrication method can be translated into different designs, making it the best suited for the in-mouth sensing environment.

C. Teeth Contact-Induced Vibration Detection and Profiling

The contact between upper and lower teeth induces impulsive vibrations. Figure 4 shows an example of teeth contact-induced vibration signals captured by the four piezo sensors installed as shown in Figure 2 (d). The impulsive part of the signal contains higher signal energy compared to the segment that captures only ambient vibration/noise. As a result, we model the impulsive event detection as an anomaly detection problem with the Gaussian noise model. We apply a sliding window on N channels of raw data, and at time step i we have sliding window signals w_1^i,...,w_N^i. We calculate window signal energy at time step i as $SE^i = \sum_{j=1...N} w_j^i \cdot w_j^i$. Then the anomaly detection is conducted on the window signal energy. We first calculate the mean μ_{noise} and standard deviation σ_{noise} of the window signal energy over the noise signals. Then we compare the incoming data's window signal energy SE^i to the noise model $\mu_{noise} + th \times \sigma_{noise}$, where th is the threshold that determines the sensitivity of the detection. If $SE^i > \mu_{noise} + th \times \sigma_{noise}$, we consider the window at time step i an event.

In this paper, we conduct teeth occlusion condition monitoring via load profiling. We consider relative signal energy of sensors placed at N different positions (i.e., $S_j, j = 1...N$) as the feature. The relative signal energy (SE) for each sensor is calculated as the captured signal energy normalized by the one with maximum average signal energy.

V. Experiments and Evaluation

To validate our design and hypothesis, we conduct real-world data collection with articulators and dental teeth models. We consider binary occlusion conditions for each dental teeth model – natural and near-optimal functional occlusion. We define the **natural functional occlusion** as the teeth contact condition recorded with the wax bite register when the patient is in a natural state. We define the **near-optimal functional occlusion** as when the mandible closes to the maxilla in a stable and balanced state inspected by the dental expert.

A. Teeth Model Making with Natural and Near-Optimal Functional Occlusion Conditions

We use teeth models installed on articulators to reconstruct teeth contact with varying functional occlusion conditions. Figure 5 shows the procedure of building a teeth model with near-optimal functional occlusion based on expert knowledge. First, the alginate impression material was used to duplicate the models of the patient as shown in Figure 5 (a). Then an inverted model is built with the mold and installed on the bottom part of the articulator with plaster mix depicted in Figure 5 (b). Finally, the top teeth model is installed with plaster mix as shown in Figure 5 (d).

B. Experiment Configuration

We analyze data collected from four teeth models, including two models from patients diagnosed with occlusal diseases (diseased) and two from patients who are not (non-diseased). Note that non-diseased does not mean that the person has near-optimal functional occlusion. We conducted a vertical

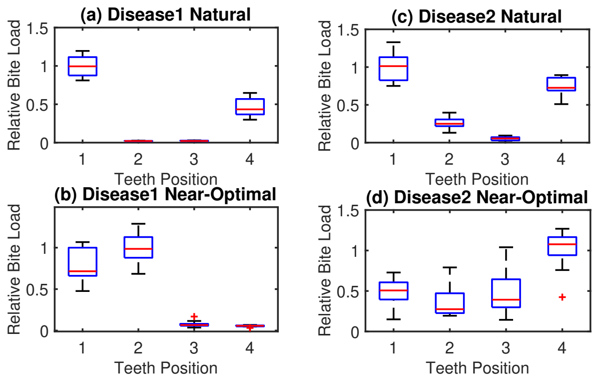

Fig. 6. Example functional occlusion profile for diseased people.

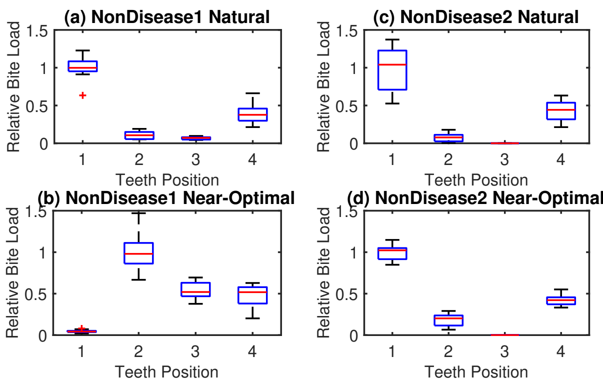

Fig. 7. Example bite profile for non-diseased people.

biting test using teeth models installed on the articulators with both natural and near-optimal functional occlusion positions as discussed in Section V-A. For each model, we conduct 10 vertical biting movements. We apply the event detection as introduced in Section IV-C, and extract signal energy as the feature for the preliminary functional occlusion profiling.

C. Results and Analysis

We demonstrate the functional occlusion profile for diseased and non-diseased models over multiple biting events and depict the profiles in Figure 6 and 7. The x-axis is the piezo sensing element locations (1 to 4), which represent the left molar, left canine, right canine, and right molar, respectively. The y-axis is the relative bite load, which we define as the normalized bite-induced vibration signal energy. For each bite event, we normalize the signal energy by the highest signal energy of all piezo sensing element locations to effectively present the front-back and left-right balances.

Figure 6 shows examples of diseased natural (Figure 6 a and c) and near-optimal (Figure 6 b and d) functional occlusion. We observe that for *Disease 1*, the natural functional occlusion has most of the load applying on the molars and almost none on canines. There is more load on the left side. For the near-optimal functional occlusion, we still observe the left-right imbalance that leans towards the left side. However, the front-back (between canine and molar) balance is reinstalled. Similarly, the *Disease 2* shows a reinstalled front-back balance in the near-optimal functional occlusion model compared to the natural one. It is worth noting that, for the two non-diseased models shown in Figure 7, *NonDisease 1* demonstrates inconsistent occlusion conditions for natural (Figure 7 a) and near-optimal functional occlusion (Figure 7 b) models, and *NonDisease 2* shows a relatively higher consistency between the natural and near-optimal functional occlusion models (Figure 7 c and d). It indicates that *NonDisease 2*'s natural occlusion conduction is closer to their near-optimal functional occlusion.

VI. Discussion

Prototype miniaturization. While the current results are promising, multiple components can be optimized to make the sensing system more suitable for the in-mouth sensing environment. In particular, we plan to reduce the sensor thickness by half to ensure that it will not discomfort users. Next, we plan to optimize the energy consumption by selecting a more energy-efficient MCU (e.g., Cortex-M) and implementing compressing algorithm and event-based sensing technique [38]. Last, after the sensor and sensing circuit is optimized, we will deploy the sensing system on human subjects. An IRB approved study will be conducted to measure the *usability*, *accuracy*, and *reliability* of the proposed solution.

Long-term monitoring for dental significance. The long-term continuous monitoring of the teeth condition brings opportunities to current dental practice. The near-optimal functional occlusion we profile in Section V-C has less to do with the symmetry of the member placement or their offsets on any axes. Rather, it focuses on the contact of teeth surfaces, and a consistent pressure formed on these surfaces from a bite. Any parallel movement of these contact surfaces may contribute toward the quality of a bite, but a less than even pressure of a bite does not necessarily dictate that a bite is not ideal. With long-term continuous monitoring of the movements, surface contacting, and balance, dentists will be able to form a better understanding of patients' habits and the health of their teeth.

A close-loop system for occlusal disease treatment. We will utilize articulators, virtual articulators, and *TeethVib*'s measurements to build a 'biting behavioral model' to ameliorate teeth occlusion conditions. In particular, the near-optimal configured by the dentist on articulators will be used as a guideline to update the structure of retainers periodically. The measurements captured by *TeethVib* will play an important role in designing effective retainers that ensure a healthy occlusion condition is maintained over time. We plan to explore reinforcement learning algorithms to build a series of updated retainers where the rewards are calculated from the improvement in the correlation between data captured from the retainer and the 'near-optimal functional occlusion' articulator.

VII. Conclusion

This paper presents *TeethVib*, a novel retainer formed teeth system to monitor teeth vibration to infer its functional occlusion. *TeethVib* leverages teeth contact-induced ambient vibration information captured by a micro piezoelectric sensor placed at the contact area between teeth and retainer. Throughout an in-lab experiment using an off-the-shelf dental articulator, we show that *TeethVib* is feasible to detect teeth occlusion conditions that are interpretable to dentists. We also discussed the remaining research challenges and potential solutions for future on-human deployments.

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