Bruxism Force Detection by a Piezoelectric Film-Based Recording Device in Sleeping Humans

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Aims: *To test the reliability and utility of a force-based bruxism detection system (Intra-Splint Force Detector [ISFD]) for multiple night recordings of forceful tooth-to-splint contacts in sleeping human subjects in their home environment.* ***Methods:*** *Bruxism-type forces, ie, forceful tooth-to-splint contacts, during the night were recorded with this system in 12 subjects (6 bruxers and 6 controls) for 5 nights in their home environment; a laboratory-based nocturnal polysomnogram (NPSG) study was also performed on 1 of these subjects.* ***Results:*** *All 12 subjects were able to use the device without substantial difficulty on a nightly basis. The bruxer group exhibited bruxism events of significantly longer duration than the control group (27 seconds/hour versus 7.4 seconds/hour, $P < .01$). A NPSG study performed on 1 subject revealed that, when the masseter muscle electromyogram (EMG) was used as a "gold standard," the ISFD had a sensitivity of 0.89. The correlation coefficient between the duration of events detected by the ISFD and the EMG was also 0.89.* ***Conclusion:*** *These results suggest that the ISFD is a system that can be used easily by the subjects and that has a reasonable reliability for bruxism detection as reflected in forceful tooth-to-splint contacts during sleep.*
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Key words: bruxism, occlusal appliance, EMG, occlusal force, sleep

Bruxism has been defined as "an oral habit consisting of involuntary rhythmic or spasmodic nonfunctional gnashing, grinding, or clenching of teeth."[1] Actual measurements of bruxism in the natural environment have typically been performed using an electromyogram (EMG) to monitor jaw-closing muscle activity in order to clarify the nature of this behavior.[2–13] In these studies, which used a 1-channel portable EMG device, data were typically collected no longer than 7 to 10 days.[10–13] These studies have provided very useful information relevant to the actual level of bruxism, but some questions require more detailed data and longer data collection periods. The primary problems with polychannel recordings performed in a sleep laboratory are the associated costs and technical complexity. For example, a nocturnal polysomnogram (NPSG) recording requires the subject to sleep at a sleep laboratory and to be wired directly to many recording devices.[3–9] Even for the 1-channel EMG-based systems, where cost and recording complexity are not the primary limitations for long-term studies, the issue of nightly electrode placement becomes a problem. It is difficult to demand that subjects clean their skin and position the electrodes precisely on the same place night after night. Garnick reported that variation of EMG recordings is a serious

problem due to the relocation of the electrodes, positioning of the head and body, and the levels of skin resistance.[14] The only alternatives are to either have the technician visit the subject's home or have the subject visit the research laboratory nightly to perform this task.

Considering the limitations of these bruxism recording systems, Takeuchi and colleagues developed an easy-to-operate recording device for sleep bruxism, which uses an occlusal appliance to measure the force being produced at the teeth.[15] This device is free of positioning variability artifacts since it fits precisely and rigidly to the teeth. These authors reported excellent sensitivity and specificity of this system for simulated bruxism behaviors during the day in a laboratory setting. The aim of this study was to extend the work by Takeuchi and colleagues and further test the reliability and utility of this piezoelectric, force-based bruxism detection system applied to sleeping human subjects.

Materials and Methods

The first part of this research involved a comparison of masseter muscle high-resolution EMG data collected during a standard NPSG study with the simultaneously recorded data from the piezoelectric detection system in a single bruxism subject. The second part involved home-based multiple night measurements in 2 subject groups (subjects with and without clinically determined bruxism). Both of these studies were approved by an ethical committee at Tokyo Medical and Dental University.

Subjects

Six suspected bruxers (4 men and 2 women, mean age 31.5 ± 3.7 years) and 6 gender- and age-matched controls (4 men and 2 women, mean age 29.5 ± 2.5 years) volunteered to participate in this research project after an informed consent was obtained. To be included in the bruxer group, an individual *(1)* had to be in good health, *(2)* had to be between the ages of 25 and 35 years, and *(3)* had to have exhibited grinding bruxism sounds during sleep in the last 6 months, as noted by his or her bed partner. Moreover, at least 1 of the following subjective criteria was required: morning masticatory muscle fatigue or pain, morning tooth soreness, or awakening during sleep due to clenching-induced jaw pain. Exclusion criteria for these subjects were *(1)* more than 2 missing teeth/quadrant (excluding third molars) and presence of gross malocclusion; *(2)* use of any prescription medication or daily alcohol; *(3)* any history or signs of an active temporomandibular disorder; and *(4)* compromised mental or physical ability. For the controls, the inclusion and exclusion criteria were the same as for the bruxers, with 2 exceptions. First, inclusion criteria number 3 was omitted. Second, an additional exclusion criterion was added as follows: *(5)* any sign or symptom suggesting the presence of bruxism; this included tooth attrition levels producing dentin exposure of the occluding tooth surfaces, tooth grinding sounds during sleep in the last 6 months (as noted by his or her bed partner), morning masticatory muscle fatigue or jaw pain, morning tooth soreness, and awakening during sleep from clenching-induced jaw pain.

Intra-Splint Force Detector System

The force-detection recording system used a 100-μm-thick deformation-sensitive piezoelectric film, which was embedded 1 mm below the occlusal surface of a modified maxillary stabilization appliance. With deformation, as would occur with any substantial occlusal force, the piezoelectric film generates an electric signal, which varies in accordance with the force applied to the film. This device was developed and described as an Intra-Splint Force Detector (ISFD).[15,16] The ISFD was connected directly to a battery-powered portable amplifier and then to a threshold-detection circuit (Micro Dynamics). This amplifier-detector generated a fixed amplitude output signal when the preset threshold was surpassed. The amplifier and threshold-detection device had a light-emitting diode (LED) which was turned on if threshold was exceeded. This LED allowed the experimenters and the subjects to check if the appliance was working correctly. The output signal was sent to a palmtop computer (HP 200LX, Hewlett-Packard), which was programmed to record and store data in a text file at a 1-second resolution (Figs 1 and 2).

Characteristically, the piezoelectric film is best at detecting rapid changes in force, not static forces.[15] When a piezofilm is loaded, there is an initial brief but transient strong signal increase which is followed by a lower-level stable signal increase. This load-induced signal increase is extremely stable as long as the load is constant. When the load is removed, there is again a brief, transient strong signal increase followed by a return to baseline level. Even for a small load level increase, the transient signal increase is easily detected, but the steady-state signal may be more difficult to be detected over time. Fortunately, bruxism events tend to be of short duration and

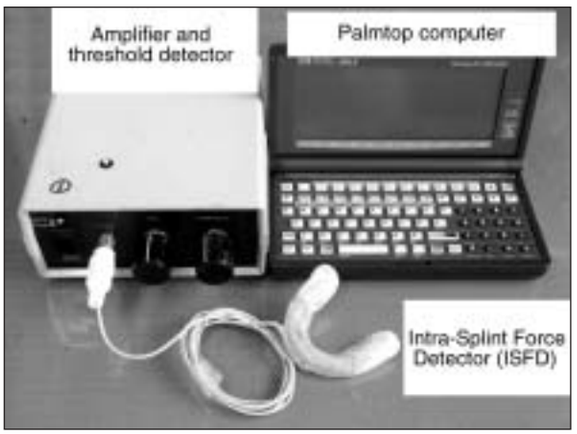


Fig 1 ISFD-palmtop system.

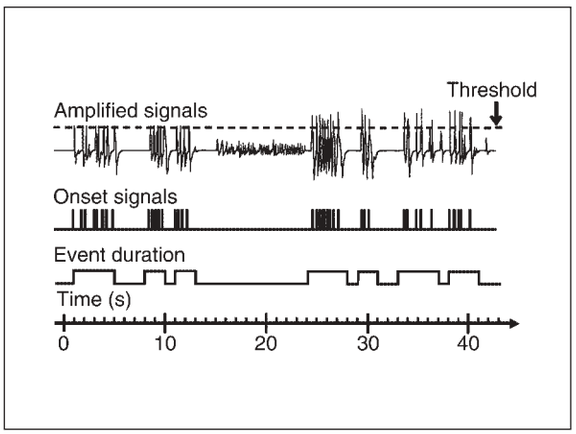


Fig 2 The plot shows the raw piezoelectric film signal (top) with the threshold level. The middle trace shows the positive on-off signals triggered by a threshold crossing. Every threshold crossing ISFD signal generates an onset signal, which is then stored in a text file of a palmtop computer with a 1-second resolution.

only a few of them are prolonged, steady-state clenchings.

Home-Based Measurements

At first, subjects were instructed on how to use the device until they became familiar with its handling. The threshold level for the bruxism detection was set at an arbitrary value of 15% of maximum voluntary contraction (MVC) to exclude any recording during swallowing and light (nonclenching) tooth contact on the appliance.[15] Prior to the actual recording, the subjects used the appliances for 5 days in order to adapt to sleeping with the occlusal device, which was connected to the amplifier. During the adaptation period the palmtop computer was not turned on. The only adverse effect of the device was some discomfort of the teeth (device too retentive) on the first 1 or 2 nights; when reported by the subject, the discomfort was then relieved by adjustment of the device. The subjects also received an Epworth sleepiness questionnaire[17] to quantify their daytime sleepiness on the first and final days of this adaptation period.

After this habituation period, ISFD measurements were performed in the subject's home for 5 nights. At the end of the fifth night the subject returned the palmtop computer so that the data could be downloaded into the laboratory computer. Throughout the experimental period, all subjects were asked to fill out a sleep questionnaire upon awaking in the morning. The following questions were asked: "What time did you go to bed last night?", "How long did it take to fall asleep last night?", and "What time did you wake up this morning?"

Based on the sleep diary, the sleeping period was first determined in order to analyze only the tooth-to-splint contacts that occurred during sleep. The second-by-second recorded ISFD signal was conditioned by interval criteria; ie, any 2 events with less than a 3-second interval were combined and considered a single event. After this conditioning, 3 outcome variables were determined for each night: the total event duration per hour (duration/hour), the total event number per hour (number/hour), and the average duration per event (averaged event duration). All these variables were averaged over the 5 nights and the differences between the 2 groups were analyzed statistically by means of a 1-way analysis of variance (ANOVA). To correct for multiple comparisons, Bonferroni-adjusted probability levels were employed ($P < .013$). Lastly, the Epworth sleepiness scores (ESS), which were obtained before and after the adaptation period, were compared to evaluate if the ISFD had a significant effect on the subjects' daytime sleepiness (paired t test, $P < .05$). A significance level of $P < .05$ was chosen to test for statistical differences.

Nocturnal Polysomnogram Study

A 35-year-old man from the bruxism group underwent a NPSG study in an audiovisually controlled dark, partially soundproof, temperature-controlled recording room. The scored NPSG recording was preceded by an adaptation night in the sleep laboratory. The following parameters were recorded continuously: the electroencephalogram; the electrooculogram; the EMG of the mentalis, anterior

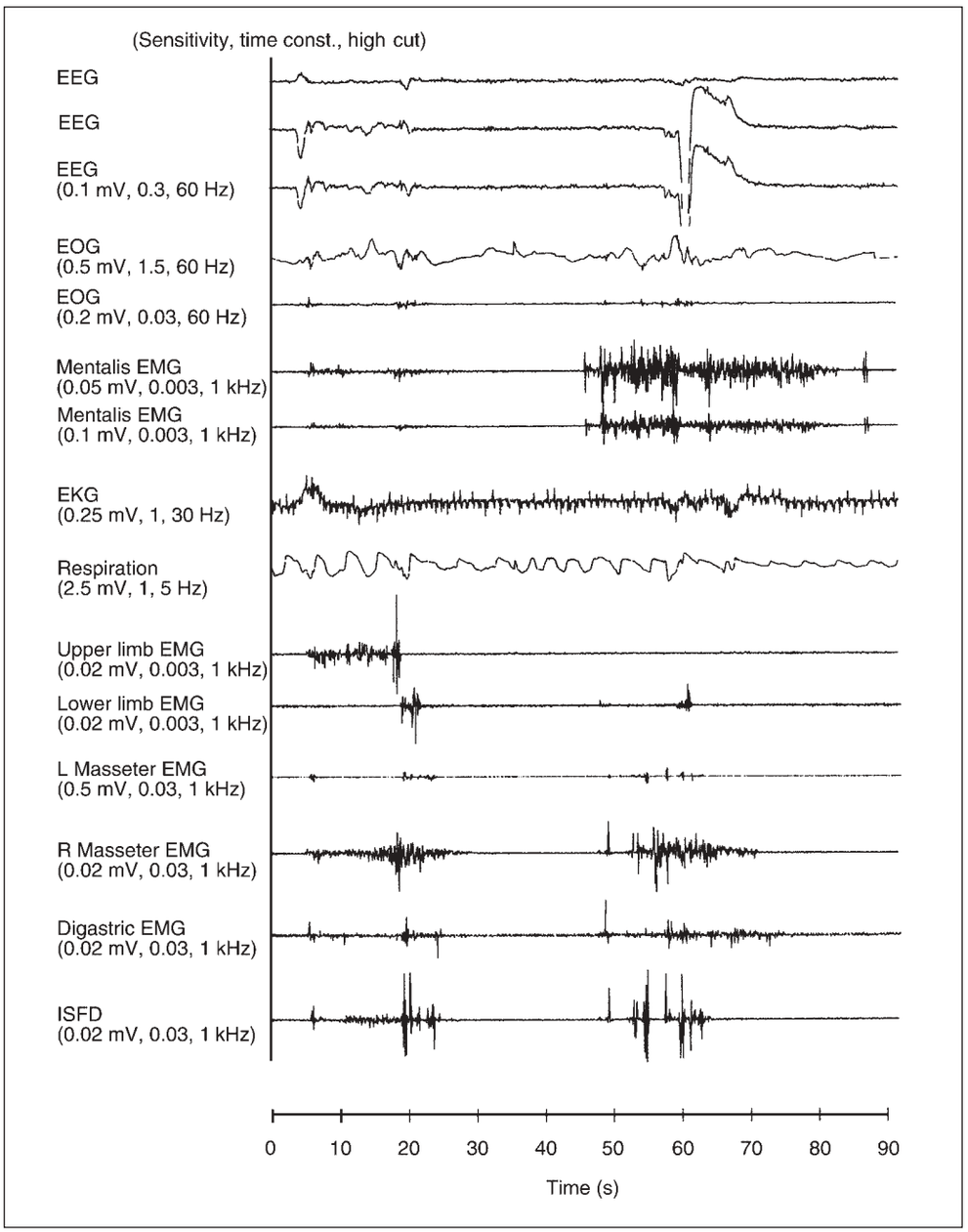


Fig 3 Parameters registered during the NPSG recording session. The raw piezofilm signal (ISFD) is depicted at the bottom and the right masseter muscle electromyogram (R Masseter EMG) corresponds to the third trace from bottom. EEG: Electroencephalogram; EOG: Electrooculogram; EKG: Electrocardiogram.

tibialis, masseter, and digastric muscles; the heart rate; the respiration; and the ISFD signal (Fig 3). All amplified analog signals were digitized with 16-bit resolution at a sampling frequency of 1562 Hz by a digital data recorder (PC116, Sony) and stored on a digital audiotape. At the beginning of the recording session, the subject was asked to perform 3 times a MVC in intercuspal position, each lasting 3 seconds.

Conventional sleep staging was performed based on standard guidelines[18] by an expert at Tokyo Medical and Dental University, and every sleeping period was analyzed. Bruxism events were determined independently from both the right masseter EMG and the ISFD signals. The raw EMG signals were first visually analyzed and every EMG signal elevation judged to be a fluctuation of the baseline level, which was regarded as an artifact signal due

Table 1 Sleep Stages and Bruxism Events Detected by the ISFD

Sleep stage	Total time (min)	Percent	No. of events	Percent
1	9	2.9%	15	20.8%
2	210	64.8%	37	51.4%
3	44	13.6%	6	8.3%
4	17	5.3%	0	0%
REM	44	13.5%	14	19.4%

REM = rapid eye movement.

to electrode movements, was excluded manually. Then, the root mean square value of the EMG signal was calculated, the EMG portions exceeding an arbitrary threshold of 5% MVC were selected, and the minimum interval and duration criteria (3 and 1 seconds, respectively) were applied to these EMG portions to determine the number and duration of the bruxing events.

To simulate the ISFD-palmtop system, the root mean square value of ISFD raw signals exceeding an arbitrary threshold of 15% MVC level was analyzed with a 1-second resolution and conditioned as described above.

The bruxism events recorded by the ISFD were visually compared with those determined by EMG. Every ISFD event which concurred with a EMG event was considered a true-positive event. Those events detected only by the ISFD or only by EMG were considered as false-positive and false-negative events, respectively. Sensitivity was calculated from the numbers of true-positive and false-negative events to evaluate accuracy. Further, only the true-positive events were used to calculate the correlation coefficient between duration of events detected by EMG and ISFD. Lastly, the duration of events recorded by the ISFD was divided by those obtained by EMG to calculate the duration ratio in order to evaluate precision.

Results

NPSG Study

The effective sleeping time (period from sleep onset to awakening minus awake time) was 5.4 hours. From the masseter muscle EMG data, 73 events for a total time of 413 seconds were detected. The event number/hour was 13.5 and the average event duration was 5.7 seconds. One EMG elevation was judged to be an artifact signal and excluded from analysis. From the ISFD data, 72 bruxism events for a total time of 336 seconds were recorded. The event number/hour was 13.3 and the average event duration was 4.7 seconds. When bruxism events detected by EMG were considered as an internal "gold standard," the numbers of true-positive events, false-negative events, and false-positive events detected by the ISFD were 65, 8, and 7, respectively. The sensitivity of the ISFD was 0.89. It was impossible to calculate the specificity since data were collected from a single subject and the EMG data (gold standard) yielded zero true negatives, thus making this calculation illogical. Lastly, the comparison of the durations of the 65 true-positive events, obtained with the 2 methods, yielded a correlation coefficient of 0.89. The duration ratio (ISFD/EMG) was 0.81, with the ISFD data being of slightly shorter duration. The prevalence of bruxism events in each stage of sleep is presented in Table 1. Note that 72.2% of the bruxism events occurred during stages 1 and 2.

Home-Based Measurements

Event duration data from the ISFD-palmtop system are shown in Fig 4. These figures show a day-by-day variation of bruxism events that occurred in an almost random fashion across the night, and furthermore, without a reproducible pattern among nights. The 3 outcome variables for both the bruxer and control groups are shown in Table 2. Statistical analysis revealed that the mean duration of events and the duration of events/night were significantly greater in the bruxer group than in the control group.

The ESS obtained at the beginning and at the end of the adaptation session are shown in Table 3. No subject exhibited a significant elevation of this score and there were no statistically significant differences between the data obtained before and during the adaptation period.

Discussion

This study evaluated the reliability of the ISFD recording system by comparing the data obtained by means of this system with those recorded by means of the masseter EMG during a NPSG study. In accordance with the Takeuchi et al study,[15] in which bruxism was simulated in awake subjects, this study also found a good concordance between the EMG and the ISFD recorded bruxism events in a sleeping subject. The NPSG study revealed that, when the masseter muscle EMG was used as a "gold standard," the sensitivity of the ISFD was 0.89. Although it is impossible to calculate specificity,

Table 2 Event Duration, Number of Events/Hour, and Event Duration/Hour (Means and Standard Deviations) for Bruxer and Control Groups

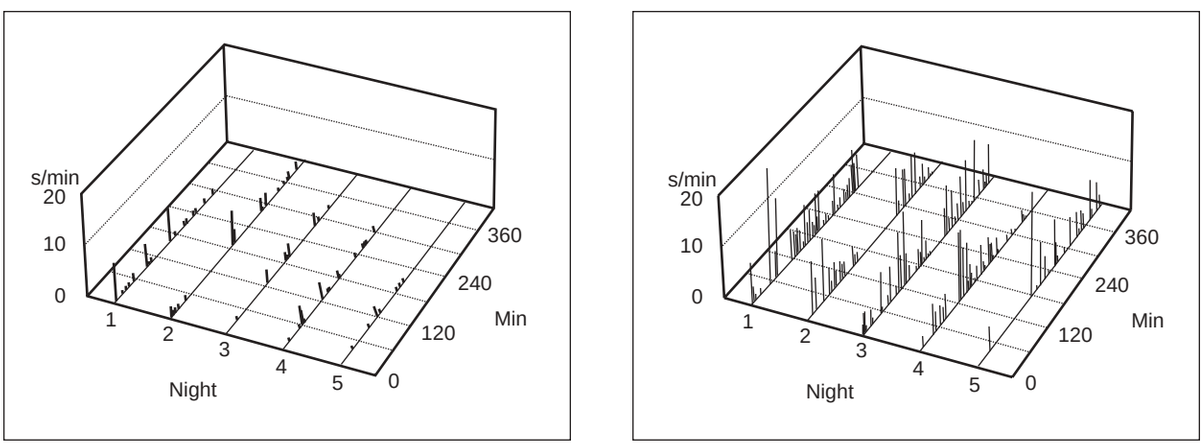
	Bruxer (n = 6)	Control (n = 6)	*P* value
Average event duration (s)	3.2 ± 0.78	1.5 ± 0.49	.002*
Number/hour	8.4 ± 2.5	4.2 ± 3.4	.035
Duration/hour (s)	27.0 ± 12	7.4 ± 7.3	.007*

*Statistically significant difference (1-way ANOVA, Bonferroni-adjusted probability levels; $P < .013$).

Table 3 Epworth Sleepiness Scores

N	ESS (mean ± SD) Before	ESS (mean ± SD) After	Mean difference	*P* value
12	7.7 ± 12.8	7.8 ± 15.5	0.080	.820

Paired *t* test; *$P < .05$.



Figs 4a and 4b These 3-D graphs show minute-by-minute data over 5 nights. Each row represents a separate night, and the oblique lines represent total event time above threshold for every minute of recording. Plot A *(left graph)* shows the data recorded from a control subject and plot B *(right graph)* from a bruxer.

90% of the ISFD events (65 out of 72 events) were true positive. Finally, the correlation coefficient between the event durations detected by the ISFD and EMG was quite high ($r = 0.89$).

Reliability was also assessed by comparing the ISFD data gathered over multiple home-based sleep recordings from 2 groups of subjects (bruxer and control subjects). The bruxer group exhibited significantly longer bruxing events than the control group. This expected substantial and significant difference adds credibility to the ISFD method as a technique to record bruxism behaviors. However, it must be noted that the method records "forceful tooth-to-splint contacts above a threshold" and therefore not necessarily bruxism. Further studies in a sleep laboratory with NPSG, video, and audio recordings are necessary to analyze if the forceful tooth-to-splint contacts recorded with the ISFD method are actually bruxism events.

All 12 subjects were able to handle the ISFD without substantial difficulty and could complete the measurement session. This observation testifies that the system is easy to use. We recognize that recording of masseter muscle activity during sleep is a more common methodology for monitoring bruxism. However, we elected to develop an occlusal appliance-based force detection system because this system should be insensitive to night set-up errors and be easily operated by the subjects themselves. Basically, an appliance-based recording system is as easy to use as putting the appliance in the mouth and turning the switch on. Such a claim cannot be made with confidence for masseter EMG recordings that require subjects to prepare their skin and apply the electrodes in a reproducible manner every night without the assistance of a research technician.

Although we could not perform a statistical analysis to see if bruxism occurred preferentially in one particular sleep stage, in our subject bruxism occurred most often in stages 1 and 2. These results are in agreement with recent studies, which reported that 71% to 88% of all bruxism episodes were detected in stages 1 and 2.[7,8]

A limitation of our detection system is the use of an occlusal appliance that has the potential to

disturb the patient's sleep quality and, more importantly, to alter the nocturnal bruxism behavior. A comparison of the ESS obtained at the beginning and the end of the adaptation period revealed no difference in daytime sleepiness. The effect of the appliance on the bruxism behavior could not be assessed during this study, and it must be recognized that the use of an occlusal device can alter it, therefore being a potential source of error. However, we believe that it is possible to minimize the short-term bruxism suppressive effect of the appliance by delivering it 1 or 2 weeks before measurements begin. During this period, patients habituate to the device and typically the bruxism behaviors reestablish themselves, as evidenced clinically from the continuation of the splint wear. Finally, in defense of the need for an alternative method for measuring oral motor behaviors, we wish to point out that surface EMG is subject to baseline drift problems across the night as the electrode paste dries and skin resistance changes.

In summary, the results of this study suggest that the ISFD-palmtop system will allow a better understanding of the variations and fluctuations of tooth-to-splint contacts above threshold in the natural environment over long periods of time. The use of this system in chronic bruxers, who have used an occlusal appliance without any success, is a most reasonable application. In such patients, this system will allow for the evaluation of various therapeutic agents and the use of counter-stimulation methods utilizing auditory, vibratory, and electric stimuli.[19–22]

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