Reproducibility of Temporomandibular Joint Clicking

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Aims: *To investigate the stability of temporomandibular joint (TMJ) clicking over a 10-day period and the effect of different open/close velocities on sound amplitude and power spectra in a group of subjects with subjectively stable unilateral clicking during the 3 months preceding the recordings.* **Methods:** *Ten volunteers were recorded with a self-developed microcomputer-based system used in a previous study on asymptomatic subjects. The recordings were performed during 4 different sessions at 3 different open/close rates in each session. The subjective sound intensity was measured with a 100-mm visual analog scale (VAS). The VAS scores, the maximum amplitudes, and the power spectra of the signals were tested for statistical differences among the different open/close rates and over the sessions. The reliability of measurements was also calculated.* **Results:** *The maximum amplitude and the power spectra of the TMJ clicking varied between subjects in a broad range that differed from those reported for asymptomatic subjects. No statistically significant differences were found within subjects for the subjective VAS scores for the maximum signal amplitudes or for the power spectrum parameters among the open/close rates and over the 4 sessions. For all 3 open/close rates and for the 4 sessions, a good to excellent reliability of measurements was determined, the values of r being mostly over 0.75.* **Conclusion:** *Within the limits of the experiment, TMJ clicking was subjectively and objectively stable over a period of 10 days. Therefore, the constant subjective perception of sound intensity was supported by the objective measurements.*
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Key words: temporomandibular joint clicking, reproducibility of results, sound spectrography, temporomandibular joint

Temporomandibular joint (TMJ) sounds are considered to be a sign of intra-articular disorders.[1–12] According to epidemiologic studies, 12% to 65% of persons examined have and/or have reported TMJ sounds.[2,13,14] This large variation is due to differences in the methods of investigation used (ie, stethoscope or palpation) and in the sample selection (ie, sound analysis in temporomandibular disorder [TMD] patients compared with randomly selected subjects).

Qualitative and semi-quantitative methods have been developed for TMJ sound classification, but the criteria presented are completely inhomogeneous.[7,15–19] For instance, one classification proposed the differentiation of sounds based on their subjective quality (soft clicking, hard clicking, cracking, crunching, grinding, grating, popping, hard crepitus, and soft crepitus) and on its time of occurrence during the open/close cycle (opening clicking, closing clicking, reciprocal clicking, terminal clicking, etc).[18] Another classification suggested the division of sounds according to their etiology, ie, to disc displacement or to osteoarthrosis.[19] This broad variety of criteria makes valid comparison between different research reports very difficult, if not impossible.

Thus, to develop more objective criteria for defining TMJ sounds, electroacoustical systems have been developed.[1,5–8,11,12,15,16,18–27] These systems allow the characterization of TMJ sounds to be made in 2 ways: in the time domain, by measuring the occurrence and duration during the open/close cycle, and in the frequency domain, by calculating the power-frequency spectrum.[8,12,19,22–24,28,29] According to different authors,[8,12,20,22,24,29–31] such an analysis should provide a non-invasive technique to diagnose TMJ sounds, notwithstanding the fact that normative data on amplitude, peak frequencies, and power spectra do not exist in the literature. This is a result of the lack of standardization in acquisition systems and signal processing, as well as in the procedures for experimental recording (eg, the speed of mandibular movements). In addition, only 1 paper has reported on the baseline values of sounds without mandibular movements.[28] As a consequence, it is impossible to compare the results of different quantitative studies.

The aim of this study was twofold: first, to investigate whether TMJ clicking sounds remained constant over a 10-day period in a group of subjects with a subjectively constant clicking during the 3 months preceding the recordings, and second, to analyze the effect of different open/close velocities on the amplitude and power spectra of the sounds.

Materials and Methods

Subjects

Ten subjects (10 females, mean age 29 years, range 19 to 41 years) were selected from the patient pool of the Clinic for Masticatory Disorders and Complete Dentures, Center for Oral Medicine and Maxillofacial Surgery, University of Zurich. For patient screening, a medical and stomatognathic history was recorded prior to the clinical examination according to departmental protocol.[32] Subjects were asked questions about pain or sounds in the TMJ, muscle pain and fatigue, impaired jaw mobility, facial pain, headache, and toothache. Subjects who reported pain-free unilateral TMJ clicking were asked to fill in a questionnaire in which they identified the side of the sound, the duration of its existence, and its constancy. They also underwent a clinical examination to screen out other signs of myoarthropathies of the masticatory system, ie, of TMD.

The clinical examination included the measurement of active and passive mandibular mobility (opening, laterotrusion, and protrusion); palpation of the TMJs; auscultation of the TMJs; and palpation of the masticatory, neck, and shoulder muscles. Passive jaw mobility was measured for all movements by applying a gentle manual force at the end of the maximum active movement. The symmetry of open/close movements was checked visually by means of a ruler held in the midsagittal plane in front of the patient. The ruler was also used to measure the movement capacity of the mandible to the nearest 1 mm. The palpated masticatory muscles were the temporalis muscle, with its insertion at the coronoid process; the deep and superficial parts of the masseter muscle; and the medial pterygoid muscle at its insertion at the mandibular angle. Tenderness to palpation was considered positive if the subject stated pain or discomfort or if the palpation evoked a clear reaction such as a palpebral reflex. Palpation pressure was not calibrated.

To be included in the study, the subject had to have pain-free unilateral TMJ clicking with a constant sound intensity during the 3 months preceding the recordings and a lack of other signs and symptoms of TMD. Thus, active opening had to be larger than 40 mm (distance between the incisal edges including overbite), protrusion and laterotrusion greater than 7 mm, side deviation at the end of maximum opening of less than 2 mm, and the difference between the active and passive jaw mobility of approximately 2 mm for opening and 1 mm for laterotrusion and protrusion.[2,32,33] In addition, tenderness to TMJ and muscle palpation had to be negative.

An informed verbal consent to participate in the study was obtained from all subjects. The project was approved by the local ethics committee.

Recording Equipment

Joint sounds were recorded by means of 2 miniature capacitor microphones with a linear response between 20 Hz and 2 kHz (Beyer MCE 5, Eugen Beyer Elektrotechnische Fabrik GmbH & Co). The microphones (diameter 7 mm, length 23 mm) were built into the earpieces of a medical stethoscope. The microphones were tested by recording a sound of 85 dB_{SPL} (sound pressure level) and 100 dB_{SPL}, and the resulting spectra were corrected to obtain a perfectly linear frequency response. Sound signals were preprocessed and pre-amplified by means of self-developed hardware consisting of amplifiers and filters. A sampling frequency of 10 kHz was chosen for each sound channel. A high-pass filter with a cut-off frequency of 50 Hz and a slope of 60 dB/decade was used for suppression of artifacts resulting from respiration and blood flow. Noise resulting from aliasing and skin friction was eliminated by low-pass filtering of the signals at 2 kHz with a slope of −80 dB/decade. The system was calibrated before every recording with a built-in sine signal generator to compensate against warm-up and other electronic drift.

The TMJ sounds were recorded and stored with a self-developed system based on an IBM-compatible personal computer and an analog-to-digital conversion board (DT2821-A, Data Translation Inc). The software was developed to optimize the speed of the data conversion hardware. Direct data storage on the hard disk by means of the direct memory access (DMA) feature was implemented on the analog-to-digital conversion board. A digital-to-analog playback feature allowed the sound signals to be heard. Further details of the recording technique are reported in a previous study.[28]

For the determination of the occurrence time of the TMJ sound during the open/close cycle, jaw movements were recorded by means of a simple, self-developed jaw-tracking device based on 2 Hall sensors. These were fixed to an aluminum bar running in the craniocaudal direction in front of the patient and attached to a spectacle frame. The Hall sensors detected variation in the electromagnetic field caused by the movement of a magnet attached to the patient's chin by means of adhesive tape. This tracking device measured only the relative and not the absolute position of the mandible. These motion data and the sound were recorded simultaneously with the software described above.

Experimental Recording Technique

The subjects sat in a conventional dental chair in a non-anechoic room. Care was taken therefore to minimize environmental noise during the recording. After the medical stethoscope was inserted into the meatus of the auditory canal, the spectacle frame of the jaw-tracking device placed, and the magnet attached to the chin, the subject was asked to perform 3 series of 6 maximum open/close movements, each of which began and ended in maximum intercuspation. Each series was interrupted after 3 movements for 2 minutes. The first series of 6 cycles was recorded at a rate of 1 Hz, the following series was recorded at 0.5 Hz, and the last series was unpaced (ie, "deliberate" rate). Between series at different rates, the subject relaxed for 5 minutes with the stethoscope and the jaw-tracking device removed. The pace was displayed to the subject by means of a light-emitting diode array moving up and down at the chosen frequency with a 1:1 ratio between the duration of the opening and closing phases. Before recording, the subject was trained to open and close at the given rate with the recording device and the jaw-tracking device in place. To screen out spurious signals, after each recording the signals were first viewed on the computer monitor (thus mainly showing low-frequency contamination) and then played back on the loudspeakers (thus easily detecting environmental noise). Contaminated recordings were discarded and the recordings were repeated. Recordings were performed with the same protocol during 3 further sessions, ie, 2, 6, and 10 days after the first examination.

Before and after each series of recordings, the subjects completed a questionnaire to evaluate subjectively whether the intensity of the clicking sound had remained constant since the previous recording session and whether it had changed during the actual recording session. In addition to answering positively or negatively to these 2 questions, the subjects evaluated the intensity of the clicking sound on a 100-mm visual analog scale (VAS), in which 0 mm represented total lack of TMJ sound and 100 mm represented the loudest TMJ sound imaginable.

Data Analysis

Half-cycle duration (T_O) was determined by interactively placing the cursor on the intersection between the ascending and descending parts of the jaw-tracking curve and a horizontal line placed at 50% of the maximum amplitude of the movement. The software calculated the relative time values of the chosen points. T_O was determined by calculating the difference between these values. For each series of movements the arithmetic mean and standard deviation of T_O were calculated.

The maximum amplitude of the signal in the time domain was also determined interactively by placing a cursor on the point where the software showed the highest peak of the sound signal. The amplitude values were expressed in volts.

For the frequency analysis, a time window was centered around the sound amplitude maximum of each open/close cycle. The analysis was performed by means of a fast Fourier transform (FFT) based on the Cooley-Tukey algorithm. The computation used a 2,048-point window corresponding to a time interval of 410 ms. A Hamming window was chosen to reduce distortion resulting from signal discontinuities in the time domain. The bandwidth ranged from 0 Hz to 5 kHz, but frequencies below 50 Hz and above 1.5 kHz were discarded by band-pass filtering. Only amplitude information was processed, and no phase relationship among components was considered. The amplitude of the frequency components was expressed in volts. The power spectrum was linearly weighted, ie, with no correction for reduced ear sensitivity at frequencies below 500 Hz and especially below 200 Hz. The frequency analysis calculated the frequencies at which 10%, 25%, 50%, 75%, and 90% of the total spectral power occurred (F_{10}, F_{25}, F_{50}, F_{75}, F_{90}) and determined the bandwidths between 10% and 90% as well as between 25% and 75% of the total power (B_{10-90}, B_{25-75}).[28] These parameters were expressed in hertz and characterized the shape of the power spectra for every subject. The parameters were used to analyze whether the shape of the power spectrum varied with statistical significance between different open/close velocities, between series during the same session, and between sessions.

Statistics

Differences between the VAS values of the sound intensity, the durations of the opening phases, and the maximum amplitudes of the sound signal were analyzed statistically by means of analysis of variance (ANOVA) for repeated measurements at a significance level of $P = 0.05$.

The ranges within which the parameters F_{10}, F_{25}, F_{50}, F_{75}, F_{90}, B_{10-90}, and B_{25-75} of the power spectra varied were normalized as a percentage of the overall mean value (mean value = 100%), and their variation range was determined. In addition, the standard deviation was calculated for each of these parameters as a percentage of the mean value.

The intraclass correlation coefficient of reliability (r) and its confidence interval were used to check the degree of reproducibility of the VAS values and of the different sound parameters. It was calculated according to the literature.[34] In general, values of r below 0.4 are considered to represent poor reliability, values between 0.4 and 0.75 represent good reliability, and values above 0.75 represent excellent reliability.[34]

Results

Self-Evaluation

All 10 patients reported that the clicking sound was constant over the 4 sessions and within each session. The VAS values for the intensity of the clicking sound are given in Table 1. These values did not show a statistically significant variation, either between sessions or within sessions ($P > 0.05$). Between sessions, r was 0.77, with a confidence interval of $r > 0.56$ ($P = 0.05$). Within sessions, r was 0.9 and its confidence interval was $r > 0.7$ ($P = 0.05$). These good-to-excellent confidence intervals confirm the subjective sound stability reported orally.

Cycle Duration

The group means and standard deviations of the half-cycle duration in each session for each opening rate are listed in Table 2. During the 4 sessions, group means varied between 1.03 ± 0.14 seconds and 1.08 ± 0.09 seconds for the 0.5-Hz rate and between 0.53 ± 0.06 seconds and 0.55 ± 0.05 seconds for the 1-Hz rate. At the deliberate rate, the group mean values varied between 0.73 ± 0.12 seconds and 0.79 ± 0.22 seconds. The statistical evaluation showed that, despite the intersubject differences, the duration of the opening phase remained constant over all 4 sessions at the 0.5-Hz, 1-Hz, and deliberate rates ($P > 0.05$).

Amplitude

The maximum amplitudes for every patient and session are listed in Table 3. Statistical analysis showed that for each subject, the maximum amplitudes did not vary significantly over all 4 sessions ($P > 0.05$). Also, the maximum amplitudes of the clicking sound did not differ significantly between the 3 different open/close rates (0.5-Hz, 1-Hz, and deliberate) within one session. The mean amplitudes differed greatly from patient to patient, since the values varied between a minimum of 0.01 V and a maximum of 1.54 V ($P < 0.05$). Thus, the variation range between subjects was far larger than that found for the variations between sessions or velocities.

For the 0.5-Hz rate, r was 0.79, with a confidence interval of $r > 0.62$ ($P = 0.05$); for the 1-Hz rate, r was 0.85 (confidence interval of $r > 0.70$, $P = 0.05$); and for the deliberate rate, r was 0.83 (confidence interval of $r > 0.68$, $P = 0.05$). Thus, for all 3 velocities the sound amplitude had a good or excellent reliability.

Table 1 Evaluation of Clicking Sound Intensity by VAS* Before and After Each Recording Session

Subject	Time	Session 1	Session 2	Session 3	Session 4
1	Before	60	61	52	76
	After	64	63	53	67
2	Before	69	66	50	36
	After	66	58	52	47
3	Before	67	35	32	74
	After	64	63	53	67
4	Before	40	34	36	37
	After	41	37	42	39
5	Before	60	61	52	76
	After	64	63	53	67
6	Before	50	48	49	48
	After	47	53	49	51
7	Before	69	28	31	26
	After	66	18	30	24
8	Before	35	23	23	20
	After	28	20	20	19
9	Before	67	60	65	62
	After	69	71	64	66
10	Before	26	41	33	33
	After	38	41	32	30

*A 100-mm scale was used.

Table 2 Duration of Half-Cycles (Opening/Closing) in Seconds for the Different Opening/Closing Rates and for the Different Sessions

Rate	Session 1	Session 2	Session 3	Session 4
0.5 Hz	1.04 ± 0.09	1.03 ± 0.14	1.08 ± 0.09	1.05 ± 0.10
1 Hz	0.55 ± 0.05	0.53 ± 0.06	0.54 ± 0.02	0.53 ± 0.03
Deliberate	0.76 ± 0.26	0.79 ± 0.22	0.73 ± 0.12	0.77 ± 0.21

Values are expressed as mean ± SD.

Power Spectra

For statistical evaluation, the data of the actual power band (F_{10}, F_{25}, F_{50}, F_{75}, F_{90}, B_{25-75}, and B_{10-90}) and velocity (0.5 Hz, 1 Hz, and deliberate) were pooled and reliability was calculated. Within each subject, each band frequency did not vary significantly over all 4 sessions ($P > 0.05$). In addition, the frequency bands of the clicking sounds did not differ significantly between the 3 different velocities (0.5 Hz, 1 Hz, and deliberate) within one session. The values for r were distributed between 0.69 and 0.87 for the rate of 0.5 Hz (confidence intervals between $r > 0.46$ and $r > 0.75$, $P = 0.05$); between 0.57 and 0.77 for the rate of 1 Hz (confidence intervals between $r > 0.4$ and $r > 0.58$ for all but one parameter, $P = 0.05$); and between 0.74 and 0.88 for the deliberate velocity (confidence intervals between $r > 0.54$ and $r > 0.76$, $P = 0.05$). Except for the 0.5-Hz rate, the estimated r values were at a close to excellent reliability, and the confidence intervals indicated at least a good reliability.

The bands of variation for the parameters describing the power spectra are shown in Fig 1. Figure 1a shows the overall differences (ie, for the 3 rates) between maxima and minima in percent of the mean values over the 4 sessions. The smallest variation range was found for subject 2 and parameter F_{90} (22%), whereas the greatest variation range (434%) was observed for subject 10 and parameter B_{10-90}. To increase clarity because of the dependence of the maxima and minima on single extreme values, the standard deviation (also presented as a percentage of the mean value of the 4 sessions) was calculated over the 3 rates and is

Table 3 Maximum Amplitudes in Volts for Each Subject and Session

Rate/Subject	Session 1	Session 2	Session 3	Session 4
0.5 Hz				
1	1.10 ± 0.20	1.29 ± 0.20	1.52 ± 0.17	0.53 ± 0.15
2	0.05 ± 0.01	0.05 ± 0.01	0.05 ± 0.01	0.07 ± 0.02
3	0.04 ± 0.01	0.04 ± 0.01	0.05 ± 0.01	0.05 ± 0.03
4	0.81 ± 0.23	0.91 ± 0.33	0.69 ± 0.22	1.02 ± 0.20
5	1.03 ± 0.24	0.60 ± 0.37	0.33 ± 0.10	1.19 ± 0.33
6	0.28 ± 0.08	0.24 ± 0.07	0.33 ± 0.07	0.30 ± 0.10
7	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00
8	0.08 ± 0.01	0.04 ± 0.02	0.08 ± 0.04	0.09 ± 0.03
9	0.26 ± 0.06	0.30 ± 0.08	0.07 ± 0.01	0.20 ± 0.19
10	0.24 ± 0.08	0.12 ± 0.07	0.12 ± 0.01	0.16 ± 0.06
Mean	0.39 ± 0.42	0.36 ± 0.44	0.33 ± 0.47	0.36 ± 0.42
1 Hz				
1	1.54 ± 0.08	1.48 ± 0.10	1.52 ± 0.22	0.57 ± 0.17
2	0.08 ± 0.02	0.07 ± 0.02	0.07 ± 0.01	0.07 ± 0.01
3	0.09 ± 0.04	0.04 ± 0.01	0.02 ± 0.01	0.05 ± 0.02
4	0.74 ± 0.25	0.78 ± 0.23	0.75 ± 0.20	0.96 ± 0.43
5	0.85 ± 0.33	0.54 ± 0.15	0.34 ± 0.07	0.87 ± 0.25
6	0.31 ± 0.15	0.59 ± 0.17	0.54 ± 0.11	0.39 ± 0.27
7	0.02 ± 0.00	0.02 ± 0.00	0.01 ± 0.00	0.01 ± 0.01
8	0.08 ± 0.07	0.03 ± 0.01	0.02 ± 0.01	0.06 ± 0.02
9	0.32 ± 0.03	0.14 ± 0.03	0.05 ± 0.02	0.10 ± 0.02
10	0.18 ± 0.06	0.21 ± 0.05	0.20 ± 0.02	0.22 ± 0.06
Mean	0.42 ± 0.49	0.39 ± 0.47	0.35 ± 0.48	0.33 ± 0.36
Deliberate velocity				
1	1.18 ± 0.20	1,22 ± 0.17	0.44 ± 0.16	0.99 ± 0.43
2	0.06 ± 0.02	0.08 ± 0.04	0.05 ± 0.01	0.08 ± 0.01
3	0.06 ± 0.03	0.03 ± 0.01	0.02 ± 0.01	0.07 ± 0.10
4	0.84 ± 0.20	0.98 ± 0.26	0.88 ± 0.23	1.01 ± 0.22
5	0.87 ± 0.20	0.57 ± 0.31	0.32 ± 0.09	0.87 ± 0.20
6	0.37 ± 0.09	0.46 ± 0.08	0.43 ± 0.08	0.45 ± 0.15
7	0.02 ± 0.00	0.02 ± 0.00	0.02 ± 0.01	0.01 ± 0.00
8	0.06 ± 0.01	0.08 ± 0.03	0.08 ± 0.03	0.11 ± 0.03
9	0.29 ± 0.14	0.38 ± 0.10	0.07 ± 0.01	0.29 ± 0.08
10	0.15 ± 0.03	0.12 ± 0.04	0.20 ± 0.07	0.14 ± 0.05
Mean	0.40 ± 0.42	0.38 ± 0.42	0.31 ± 0.27	0.36 ± 0.40

Values are expressed as means ± SD.

shown in Fig 1b. The smallest standard deviation was found for subject 2 and parameter F_{90} (4% of the mean value) and the greatest standard deviation was found for subject 10 and parameter B_{25-75} (97% of the mean value).

Discussion

The present study describes a method for recording TMJ sounds digitally, for quantifying them in the amplitude and frequency domains, and for checking their variation over time. The objectives of our investigation were the evaluation of the constancy of TMJ clicking over a period of 10 days and the analysis of the influence of the open/close velocity on TMJ clicking. The study was performed on subjects with pain-free unilateral TMJ clicking with subjectively constant sound intensity during the 3 months preceding the recordings.

The results showed that the subjects felt the sound intensity to be constant throughout the duration of the study as well as during each session. The subjects were able to open/close at a reproducible rate of 0.5 and 1 Hz, and the unpaced (ie, deliberate) rate also appeared to be reproducible, its frequency being between the 2 fixed rates (around 0.75 Hz). The maximum amplitudes of the signal did not show statistically significant variations intraindividually, either over the duration of the study or at different open/close velocities. This resulted in a good to excellent reliability of the sound amplitudes, with confidence intervals of the coefficients (r) greater than 0.62. Also, the shapes of

Figs 1a and 1b Variation of the power spectrum parameters (F_{10}, F_{25}, F_{50}, F_{75}, F_{90}, B_{10-90}, and B_{25-75}) shown as a percentage of the mean values over the 4 sessions.

Fig 1a Difference between maxima and minima.

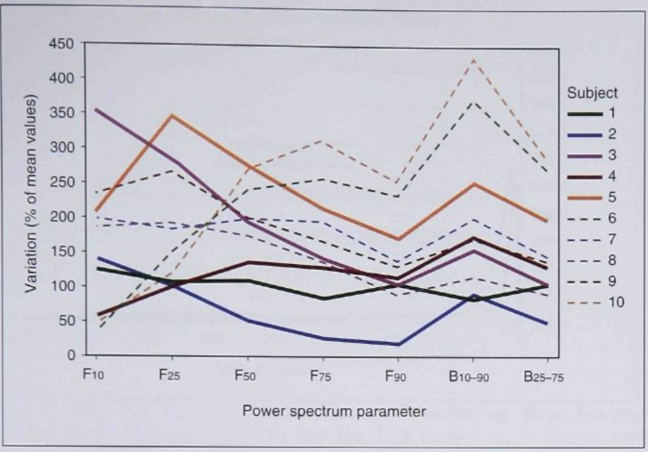
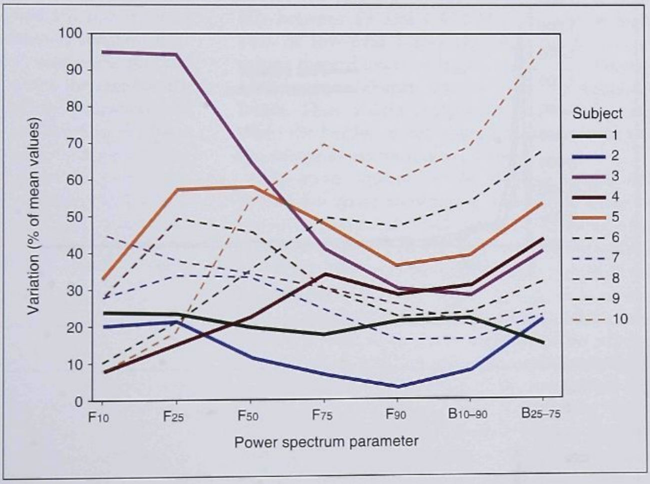
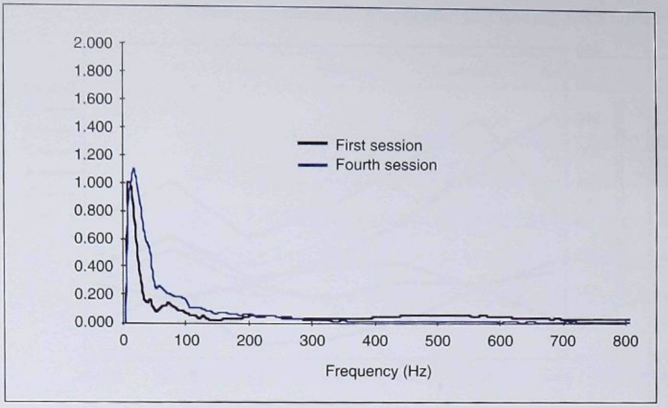


Fig 1b Standard deviations.



the power spectra did not vary significantly between sessions or between rates. The values of r for F_{10}, F_{25}, F_{50}, F_{75}, F_{90}, B_{10-90}, and B_{25-75} were good to excellent, with confidence intervals greater than 0.4. Only the confidence interval for B_{25-75} was smaller than 0.4. Thus, the subjective impression that the sound remained constant during the whole experiment is reflected in the fact that neither the open/close velocity nor the session significantly influenced the amplitudes or the frequency range of the TMJ sounds. In spite of the relatively small number of subjects, the confidence intervals of the intraclass correlation coefficients of reliability indicated a good to excellent stability of the subjective VAS scores and of the objective measurements.

The maximum amplitude and especially the power spectra varied between subjects. According to the mean of the standard deviations of the



Figs 2a to 2c Spectra of the clicking in Subject 3, averaged over all movements for sessions 1 and 4. The spectra are normalized so that the area under the curve is a unit.

Fig 2a Spectra at 0.5-Hz open/close pace.

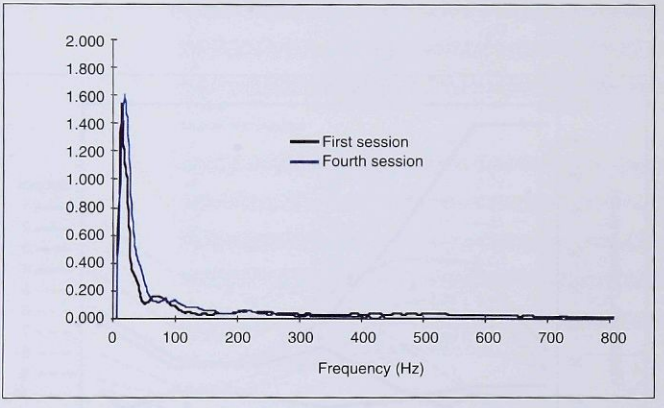


Fig 2b Spectra at 1-Hz open/close pace.

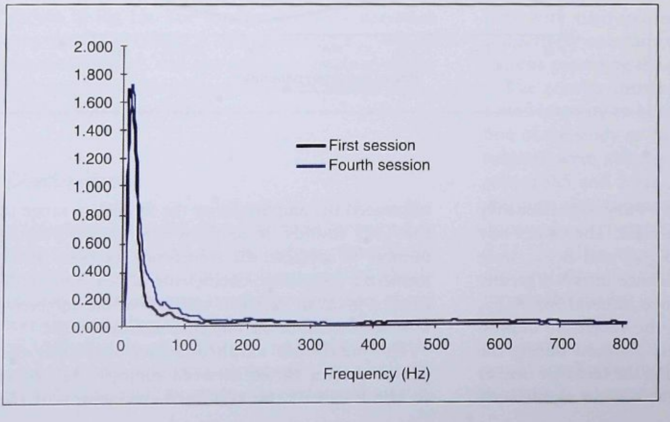


Fig 2c Spectra at deliberate open/close pace.

Table 4 Power Spectrum Parameters of the Baseline Power Spectra (Without Motion), of the Movement Spectra of Asymptomatic Joints from a Previous Study,[28] and of the Clicking Joints from This Study

Parameter	Asymptomatic baseline	Asymptomatic movement	Clicking movement
F_{10}	185 ± 10	166 ± 3	132 ± 17
F_{25}	278 ± 20	246 ± 7	214 ± 32
F_{50}	500 ± 39	435 ± 13	356 ± 49
F_{75}	851 ± 58	735 ± 22	545 ± 58
F_{90}	1316 ± 56	1078 ± 26	786 ± 56
B_{10-90}	1130 ± 53	912 ± 24	652 ± 43
B_{25-75}	572 ± 49	489 ± 18	338 ± 29

Values are expressed as means ± standard error.

power spectra parameters F_{10}, F_{25}, F_{50}, F_{75}, F_{90}, B_{10-90}, and B_{25-75} (Fig 1b), most of the subjects showed a variation of the majority of the parameters that was below 33% (subjects 1, 2, 4, 7, 8, and 9). Interestingly, the subjects with a higher parameter variation (subjects 3, 5, 6, and 10) also reported that the clicking intensity remained constant over the duration of the experiment, suggesting that the variability of the sounds recorded throughout the whole experiment was too small to be perceived by the subjects. This fact can be explained by the logarithmic perception of the ear, which requires a very high variation of sound pressure to detect any amplitude differences. Future studies should measure the subjective variation of TMJ sounds over time and verify whether the objective variation is greater than the range determined in this study. Moreover, we analyzed more closely the spectra of Subject 3, which apparently showed the greatest variation of the parameters F_{10}, F_{25}, F_{50}, F_{75}, and F_{90}, and observed substantial stability in the spectral shape for all 3 open/close rates. Figs 2a to 2c show the mean spectra over all open/close phases for each rate during the first and the fourth sessions. In spite of slight shape variations, the majority of the power appears to be concentrated below 50 Hz, and the spectral peaks differ between sessions by only a few Hz, which conforms with the subjective impression of the sounds' stability. Most of the variation of the parameters was also given by noise effects and is therefore not in contradiction to the excellent reliability of the method.

A comparison of our results with those of previous studies is difficult because different equipment and experimental procedures were used. For instance, several studies did not report whether or how the sound signal was filtered for reduction of sound artifacts. Furthermore, different bandwidths were used in former studies, eg, 48 to 205 Hz,[24] 32 to 314 Hz,[11] 58 to 465 Hz,[31] 442 to 1,090 Hz,[26] and 74 to 790 Hz.[29] In this study we analyzed frequencies between 0 and 1,500 Hz, which, due to the discrete Fourier transform, were actually between 59 and 1,430 Hz. The use of high-pass or low-pass filters can shift the frequency ranges toward lower or higher frequencies because of the unequal energy distribution of the frequency bands. Thus, a data comparison can be done only when the hardware and software characteristics of the measurement system are known.

The power spectra of the clicking sounds differed from those recorded in a previous study on subjects without TMJ sounds, both during mandibular movements and with the mandible immobile.[28] In fact, the overall mean values of the parameters F_{10}, F_{25}, F_{50}, F_{75}, F_{90}, B_{10-90}, and B_{25-75}, determined for the 10 clicking joints, were always smaller than those determined for asymptomatic joints without and with movement (Table 4). The highest mean values of the parameters F_{10}, F_{25}, F_{50}, F_{75}, F_{90}, B_{10-90}, and B_{25-75} were determined for the quite flat baseline spectra recorded without motion. Intermediate values were found for jaw movement recordings without clicking (spectral shape skewed toward lower frequencies). The smallest values were found for the recordings of the clicking joints, indicating a further spectral shape shifted toward lower frequencies.

Our study confirmed the subjective stability of TMJ sounds over a period of 10 days, the independence of the sound characteristics with respect to open/close velocity, and a very good reliability of the method itself. The TMJ sounds seem to vary between subjects over a broad range, possibly because of differences in the degree of internal derangement and/or in the shape of the disc.

Within the limits of this experiment, the constant subjective perception of sound intensity was supported by objective measurements. Furthermore, the data seem to suggest that, in longitudinal studies, the opening/closing velocity need not be standardized, provided that it ranges between 0.5 and 1.0 Hz. However, a larger number of subjects is needed to confirm this hypothesis.

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