

# Temporomandibular Joint Hypermobility - Diagnosis Based on Auscultation and Signals Analysis

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## Research article

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# Abstract

## Background

The temporomandibular joint is a well-known anatomical structure a vast majority of dentists doesn't know how to treat patients with temporomandibular disorders. What is more, even physiological sounds accompanying joint movement can deceitfully indicate pathological features. An example of TMD is temporomandibular joint hypermobility, a disorder which still requires comprehensive study and analysis.

## Methods

Forty seven volunteers were diagnosed with the RDC/TMD questionnaire and auscultated with electronic stethoscope Littmann 3200 on both sides simultaneously. Recorded TMJ sounds were sent to the computer via Bluetooth for further numerical analysis.

## Results

Two patients with TMJH were diagnosed. In the first case the RDC/TMD based diagnosis were discovered as Ia (myofascial pain) and IIIa (arthralgia). The second person was diagnosed with no disorder according to RDC/TMD questionnaire. However the RDC/TMD examination does not support recognition of TMJH. Therefore in this paper it was proved that such recognition can be performed based on the digital time-frequency analysis of the TMJ sound.

## Conclusions

TMJH is rare case, at ours research 4% patients. The recognition of dysfunction can be based on the characteristic time-frequency features presented in the spectrogram representation of TMJ sound.

## Trial registration

The Jagiellonian University Bioethics Committee gave consent for examination, number 1072.6120.71.2019 from the 24th of April 2019 year. All participants were informed about the objectives of the study. Each of them expressed their written consent to participate in the examination and signed the consent form before the study. During the procedures, the rules of Good Clinical Practice were applied and the Helsinki Declaration was followed.

## Background

The temporomandibular joint (TMJ) is an anatomical structure that chiefly consists of the mandibular condyle, temporal bone, articular disc, joint capsule, ligaments, blood vessels and nerve supply. It is a synovial joint. The functions of the TMJ and surrounding tissues and muscles are for example mastication, speech, opening, and closing during food chewing, swallowing saliva. The articular surface in human joints is formed by hyaline cartilage, but the exception is the TMJ, where fibrocartilage occurs.

During the examination, it is necessary to remember that both joints work together. The work of TMJ strictly depends on the different architecture of the mandibular condyle, muscle strength and tension, ligaments and type of occlusal contacts. Another important part of TMJ is articular disk, which participates in movements - hinging and gliding actions. The anatomical shape is oval and covered fibrous surface. The disc shape is often referred to as peaked cap. The TMJ is divided with disc into upper and lower compartment. The upper one is bigger than lower. (1). The work of TMJ also remains in direct correlation with muscles.

Biomechanics of TMJ is a complex issue and its understanding is the basis for effective diagnosis and treatment. In human body there are two seemingly independent temporomandibular joints but the fact of their connection with the mandibular bone enables them to work together. Therefore, in a complex motion system, the translation of one element results in rotation in another. The joint can be divided into 2 compartments: upper and lower. The lower consists of condylar process and articular disc which movements are limited by articular ligaments. Therefore, in this part, the only possible and physiologically correct movement is rotation. In the upper part condylar process with articular disc construct with mandibular fossa a kinematic system. Since the articular disc is not firmly fixed in articular fossa, translation in this area is possible. The articular disc is common part of both systems and functions as a non-ossificated bone without confusing with meniscus and is classified as a complex joint. In general, ligaments do not take an active part in joint movement but restrict it passively or neuromuscularly. Articular surfaces must be in constant contact, which, during the adduction and abduction movement, is ensured by the proper displacement and deformation of the disc.(2)

Each joint in the human body might be modelled in a simplistic way as a mechanical connection of a couple of lubricated surfaces, which is inevitably prone to friction. Such a condition of the movement of roughly degenerated surfaces of the joint causes energy transfer by mechanical compressions and decompressions of the matter which generates mechanical waves propagating through surrounding tissues. Depending on the frequency of these vibrations they might be classified as infra, ultra or acoustic sounds. The last ones are hearable and feature spectral range of 20Hz-20kHz. Moreover, these sounds carry diagnostic information and may be successfully used in preliminary examination of joints condition. It turns out that a healthy joint is either soundless or generates only expected physiological sounds.

It is also worth mentioning that temporomandibular articular disc plays a critical role in the context of absorbing the shocks applied to the joint and lubricating surfaces of contacting parts. The disc is generally composed of macromolecules and the lubricating medium, the various chemical composition of which results in small differences of the mechanical properties. Therefore uneven pressure distribution on the disc is observed. During the movement of TMJ, the articular disc splits the exerted pressure across the whole active area. As a result the shocks are absorbed and the condylar movement is stabilized. Therefore the mandibular disc is particularly prone to permanent wear damage, which may lead to TMD. Moreover, presumably the vast majority of temporomandibular disorders (TMD) are claimed to be caused by degeneration and perforation of the articular disc. According to Xiaoyun et.al the bone of

the skull and the mandible may be in general considered as linearly elastic. Elasticity modulus of the latter is reported to differ from cortical bone to the cancellous bone. Another important yet obvious conclusion is that deformability of the bone is much lower than deformability of the articular disc. The elasticity modulus of the mandible is reported to vary between 13000 and 7300 MPa, whilst in case of the articular disc - between 0.675 and 44 MPa. As it has already been pointed out, neither the TMJ ligaments nor the cartilage have a significant impact on the TMJ movement and hence are often skipped in the course of the of the TMJ biomechanics modelling. Many mechanical models have been proposed in the literature to investigate and simulate the undoubtedly complex biomechanics of TMJ. Usually such models are accompanied by Computer Aided Design techniques such as Finite Element Method (FEM) or Multi-body Dynamics Analysis (MDA). It turns out that a simple single-phase elastic model does not allow to express the mechanical behaviour of TMJ. As a result, the biphasic approach was suggested to describe both fluid and solid components together with accompanying viscous effect but it also features some limitations. Therefore other more promising models such as poroelastic and viscoelastic material have been introduced to fulfil the demanding and complex nature of TMJ biomechanics (3). Stress distribution practically occurring in TMJ is still not well defined because of difficulties taking place during experimental measurements. However Zhan Liu et. al. proposed a 3D model of temporomandibular joint based on the CT scans of a person without any TMD. Based on this example the strain in TMJ components was simulated with FEM in ANSYS software. The maximum Von Mises stress obtained for articular disc was 0.32 MPa in interior middle area, 0.12 MPa in anterior area and 0.026 MPa in posterior area which proves an uneven stress distribution in this part of TMJ (4).

Healthy TMJ is painless, soundless and hassle-free during chewing, speaking and eating. Acoustical effects in TMJ are related to joint dysfunction. They occur as the result of incorrect disc displacement during movement - because of the condylar head displaced from the proper position. Joint sounds have an important role in examination, diagnosis and future treatment in temporomandibular disorders. There is a wide spectrum of sounds from joints. Internal derangement of TMJ leads to clinical symptoms such as clicking, disc displacement, disc dislocation with reduction or disk displacement without reduction.

Under the term of disc displacement with reduction the situation when the articular disc has been displaced to the condylar head is understood. It can be displaced anteriorly, medially or laterally. At the time of adduction and abduction of the mandibular, acoustical effects like clicking, crepiting or thud sound can occur. The other type of TMD is known as disc displacement with intermittent locking - a situation similar to the disc displacement with reduction but with the limited opening. (5). Among TMD we also distinguish hypermobile temporomandibular joint (TMJH), which may be a disorder or physiological condition.

TMJH is a physiological state in which the correct disc position is observed but the maximal mouth opening leads to subluxation or luxation of the joint and occurs with pain. Hypermobility is commonly known as subluxation. It is a movement of TMJ during wide mouth opening. The correct anatomy of TMJ is associated with smooth condylar head movement down into the top of the articular tubercle. In the group of patients during the widest mouth opening, due to sudden skip, the temporary stop occurs.

Such a stop results in a specific death sound- thump. The phenomenon is physiological and results from the specific anatomy of the articular tubercle. Among the factors that lead to such a specific anatomy of the articular tubercle we can distinguish the excessive mouth opening during yawning, singing, vomiting, eating, factors such as generalized joint hypermobility (GJH), Ehler Danlos syndrome or Marfan syndrome and intubation under general anesthesia (5, 6). The dynamic compression during excursive gliding and incursive movements confirm subluxation (5-7).

Subluxation may also be considered a non-physiological condition if the patient reports chewing muscle disorders as well as TMJ pain and discomfort. The sound that appears in the final step of opening the mouth may be a sign of subluxation of the condyle, which moves forward(8).

When the patient has repeated episodes of subluxation, this may result in lengthening of the ligaments potentially leading to disorders of the disc.(2) TMJH may also occur as a result of injury, damage to the joint capsule. Some of the patients in addition to TMJH also have hypermobility of other joints in the body. This is known as GJH. It is greater than average range of motion in many joints. There is no single test commonly used to confirm the diagnosis of GJH(9). The various tests are used to diagnose patients, for example: Carter&Wilkinson, Kirk, et al, Beighton&Horan, Beighton, et al.(10)

TMJH has been also investigated by Nosouhian et. al.: the carried out case-control clinical study included 69 patients in the age 22-42. The main aim was to examine correlation between the etiological factors of TMJH and its relations to habitual status. Participants had the manifestation of TMJH. The researchers divided the patients into three groups based on the maximum mouth opening (measured between upper and lower incisors). 25 patients were in the group with the range 50-55mm, 18 patients with the range of 55-65mm and 26 patients with more than 65mm. All the participants filled the questionnaire concerning discomfort, pain during opening, mastication, pain in the ear, temple or neck, side of chewing and about first symptoms of TMJH. The last part of the research was a clinical examination by an oral and maxillofacial specialist. The procedures included also exam of masticatory system, facial symmetry observation, abnormalities in teeth and jaw system, palpation and auscultation of TMJ with stethoscope. Obtained results have led to the conclusion that the largest number of patients was at the age of 31-42 (70.99%), 37.67% of patients were at the age of 26 to 35 years old. What is more the researchers notice correlation between the pain in TMJ and maximum mouth opening. TMJH was observed much more frequently for women(78.2%) than men [9].

Pasinato et. al. have proven that generalized joint hypermobility (GJH) as a predisposing factor for the development of TMD. 34 women aged 18-35 were diagnosed with TMD using Research Diagnostic Criteria for Temporomandibular Disorders (RDC/TMD). GJH hypermobility was examined by Carter and Wilkinson's criteria modified by Beighton. The volunteers were divided into two groups: with hypermobility and without hypermobility. 64.71% of patients with TMD had also GJH including TMJH. Patients from hypermobile group suffer from painful mouth opening. What is more there was compatibility in higher results GJH and wider range of motion with and without pain. The prevalence of GJH was higher in group with TMD. (11) . Mehndiratta et. al. examined patients with TMJH using MR and noticed that TMJH has

been connected with an anatomic variant where the articular eminence has a steep - short, posterior slope and longer anterior slope(5)

Nowadays, a lot of attention has been paid to the development of questionnaires to examine a temporomandibular joint and new ways of diagnosing based on the adopted and modified physical methods such as e.g. auscultation, RTG, tomography CT, ultrasonography, MR and many other different investigation methods.

The RDC/TMD is commonly known and used by researchers. In this case two axis for systemized diagnosis of TMD are used. In the Axis I the clinical questionnaire is used in order to classify TMD for the further diagnosis. Each participant after examination is being diagnosed for one or both sides: group I: IA- myofascial pain, IB- myofascial pain with a limited opening, group II: IIA- disk displacement with reduction, IIB disk displacement without reduction with a limited opening, IIC- disk displacement without reduction, without limited opening, group III: IIIA- arthralgia, IIIB- osteoarthritis, IIIC- osteoarthrosis. Patients can get maximum 5 diagnosis or no diagnosis. According to axis II, patients independently fill in a questionnaire concerning psychosocial factors such as chronic pain, jaw disability checklist, depression and non-specific physical symptoms, demographic data.

Noise and other sounds associated with TMJ have been the objective of researchers for years. In 1952 Ekenstein, in 1974 Outlette and other authors recorded the performed experiments on videotape and carried out audiovisual evaluation during jaw opening and closing (12). Nowadays stethoscope is a basic and typical instrument for acoustical examination of TMJ (13) (14) (15). Another option is more advanced device created by Radke et al. The researchers invited equipment called joint vibration analysis(JVA) for diagnosing joints. The device is based on sensed joint vibrations and analysis the intensity and frequency of emitted vibrations. (16) Unfortunately the solution isn't available in our place for research.

Auscultation is a commonly used non-invasive diagnostic method. Traditional acoustic phonendoscopes have been used since the 19th century. However, nowadays digital devices facilitate many fields of science and life including clinical measurements. Therefore currently dentists take advantage of electronic stethoscopes during TMJ auscultation. Such instruments not only allow to digitally filter noise and redundant frequencies but also support acquisition of recorded signals for the further analysis. This approach allows also to incorporate digital signal processing to implement dedicated algorithms supporting detection of pathological syndromes and pattern recognition. Nonetheless, from the biomedical signals processing point of view, any kind of disorders detection requires establishing a link between medical context and digital representation of the signal. Therefore seeking for the patterns occurring in the signal which correspond with real pathologies detected by physician is usually crucial in the development of algorithms facilitating automated diagnosis. It is often difficult to find representative signal features in time domain, especially during visual evaluation of the graph. Much more useful methodology involves analysis of the spectral characteristics, which can be performed in the frequency

domain. The operation of transforming time domain into frequency domain is called Fourier Transform and is described by the following mathematical formula:

$$X(f) = \int_{-\infty}^{+\infty} x(t)e^{-j2\pi ft} dt \quad (1)$$

where:  $X(f)$  - resulting function,  $f$  - frequency,  $t$  - time,  $j = \sqrt{-1}$ .

This operation may be interpreted as a measure of the similarity between the original signal and each basic sinusoidal component. The equation (1) can be successfully used for analogue signals. However, in case of digital measurements, it is necessary to take advantage of discrete version of Fourier Transform (DFT):

$$X(f) = \sum_{n=-\infty}^{+\infty} x(n\Delta t)e^{-j2\pi(f/f_s)n} \quad (2)$$

where:  $\Delta t$  - time interval,  $f_s$  - sampling rate,  $n$  - sample number.

According to the above equation (2), the spectrum can be calculated as a sum of products of signal sample and harmonic components. This is however the particular and inverted case of generic theorem, which states that the analysed signal may be approximated by a sum of elementary (basic) signals:

$$x(t) = \sum_k a_k g_k(t) \quad (3)$$

where:  $a_k$  represents the coefficients determining the overall impact of each component,  $g_k(t)$  - elementary signals with different frequencies.

Nevertheless, in practice the considered method is efficient only for stationary signals which include periodic occurrence of a particular pattern. In this case, the overall spectrum of the signal is sufficient to evaluate all possible harmonics features. However, for non-stationary signals, which may be defined as variable in time or impulse, this method is not efficient hence it is required to provide information about frequencies present in each atomic time window. An approach which meets such requirements is called time-frequency analysis and, in general, is based on calculating the correlation between the kernel function and a signal in basic consecutive time sections. The kernel function should effectively match spectral characteristics of the original signal, i.e. if the signal is non-stationary then the kernel function should have a form of non-stationary impulse oscillation with compact carrier. The more the shape of the basic functions is similar to the original signal the less basic functions are needed to efficiently approximate the signal. An example of time-frequency analysis is the Short-Time Fourier Transform (STFT), which uses sinuses as basic functions. STFT allows to obtain the two dimensional representation of time-frequency coefficients called spectrogram with every time-frequency atom of the same dimensions and area. As the major drawback of such a result the same resolution of all

components can be treated. The step of key importance in every time-frequency analysis method is consists in selection of the appropriate window function used for slicing the time domain into atomic signal sections. The special variant of STFT, with the Gaussian function used as a window, is called Gabor Transform. More advanced methods, like Wavelet Transform, allow to obtain the lower time resolution for lower frequencies and higher time resolution for higher frequencies (Figure 1.). However, the area of all cells still remains the same. Moreover, the uncertainty principle implies that the value of product of frequency bandwidth and signal duration time cannot be lower than defined constant. In other words, the higher the frequency resolution the lower time resolution can be achieved and vice versa (17).

The required distribution of time-frequency atoms depends on the particular application, but the design of computational method shall always strive to limit the resulting area of each cell to obtain maximal resolution for both spectrogram axis. Another interesting technique of time-frequency analysis is Reduced Interference Distribution (RID). This method belongs to the general Cohen's class distributions, which constitute the generalization of Wigner-Ville transform. RID attempts to solve the parasite cross interferences occurring on Wigner-Ville representation by finding a compromise between the resolution and readability of the result. Cohen's class time-frequency methods, including spectrogram, are feasible to feature time and frequency shift invariance, which means that any time shift in the signal is reflected as an equivalent time shift in the TF distribution and any shift in the frequency of the signal is reflected as an equivalent frequency shift in the time-frequency representation. This property is often required for a successful pattern recognition procedure. Nevertheless, in some applications, either time or frequency invariance might not be desirable, i.e. in case when the time or frequency shift is relevant for feature extraction (4, 18, 19). Unlike in the case of time and frequency shift invariances, not every of Cohen's generic class distributions can be characterized by the scale covariance which ensures that the representation of both scaled and original signals is the same (20).

Widmalm et al. reported 2 major groups of sounds evoked by TMJ which could be specified with the use of the Reduced Interference Distribution (RID) - another method of time-frequency analysis. The first group consisted of three types of short-duration signals with a single energy peak below 600 Hz, from 600 to 1200 Hz and above 1200 Hz which were classified as clickings of RID type 1, 2 and 3 respectively. The second group included two types of signals which were characterized as having multiple energy peaks distributed over prolonged period of time: the clickings of RID type 4 with energy peaks in frequency range below 600 Hz and clickings of RID type 5 with peaks between 600 and 3600 Hz (17) (21). In the literature many attempts to implement automated classification method of mentioned clicking types have been presented. Reported approaches include amongst others: RID supported by Artificial Neural Networks, Adaptive Gabor transforms with the third order-Rényi number or Nearest Constraint Linear Combination (NCLC) accompanied by Neural Networks. Djurdjanovic et al. (22) placed an electret microphone with flat frequency response between 40 and 20000 Hz into each opening of auditory canal of the patient. A Reprosil polysiloxane putty was used as a cover for each microphone to attenuate external noise. Signals were recorded with 14-bit resolution at the 48 kHz sampling rate. The motivation for using such high sampling frequency was driven by literature reports indicating the analysis of TMJ should cover the whole audible spectrum from 20 to 20000 Hz. The low-pass analogue

Butterworth filter with the cut-off frequency of 20000 Hz was used in order to avoid aliasing. In the next step, the 512-point Hanning window was applied when calculating the time-frequency representation. The RID of the signal was performed based on the binomial distribution which constitutes particularly attractive discrete estimation of RID which can be computed very efficiently. RIDs of each clicking were extracted manually which constituted the drawback of the proposed method and could have been improved by implementing automated segmentation method. As a result, 35 cliclings of types 1, 31 of type 2 and 38 of type 3 were visually isolated and used for testing of implemented method. Crepitations were not considered in this research. In the next step, the authors exploited the time-shift (TIR) and time-shift scale-invariant (STIR) RID and calculated the moments of obtained representation (order 1 up to 15) as a vectors of features. Finally, the NN, ZSS and NCLC classifiers were trained and the performance of each method was evaluated. The major result showed that in case of STIR all the pattern recognition algorithms featured similar performance. Nevertheless in case of TIR the efficiency of NN was better (one misclassification for 15 instances from each clicking type) than for other techniques. It has been also concluded that exploiting scale invariance to the TMJ sounds classification deteriorates classifier efficacy, regardless of which feature recognition technique was utilized. What's more, the authors have also stated that probably more than just three TMJ clicking types can be distinguished (22) . Sungyub Yoo et al. proposed an analysis of TMJ clicking sounds using Radially Gaussian Kernels. During this research TMJ sounds were recorded during maximal jaw opening and protrusion followed by opening and closing from ten patients. The acoustic signals were acquired using two electret microphones placed in each ear canal at 15000 Hz sampling rate. The measured frequency range (initially up to 16000 Hz) was limited to 100-500Hz by a band-pass filter. In the preprocessing step signals were down-sampled to 7500 Hz. Finally six types of clickings were differentiated based on the time-frequency patterns observed in RGK distribution (22) (23) . It is also worth mentioning about the modern trend of wearable sensors, which has been a subject of interest for the scientists and commercial ventures all over the world. Toreyin H. et al. reported that this technology is not available in the context of joint sound measurement and proposed an interesting architecture of a wearable system for knee joint disorders detection based on MEMS sensors and FPGA (4, 18). Such an approach could be also considered in the regard of TMJ analysis and TMD diagnosis.

### **Aim of the study**

The main goal of the research was to examine the group of patients suffering from TMD in order to describe acoustical symptoms accompanying hypermobile temporomandibular joint and compare them with the sounds of clickings. Special attention was concerned about patients who had no recognition in RDC / TMD diagnosis.

Our second aim was also to provide a comparative analysis of mentioned disorders from digital sound processing standpoint.

Last but not least, the final goal of this research was to create the TMJ sounds database which might have constituted a reference for further research and development of computer aided TMJ diagnostic

methods as well as for educational purposes.

## Methods

The study involved patients who decided to come because of problems with the temporomandibular joints. Participants were from the area of Cracow, Poland. The participants were informed about the aim of the examination and signed consent forms. The Jagiellonian University Bioethics Committee gave consent for examination, number 1072.6120.71.2019 from the 24th of April 2019 year. All participants were informed about the objectives of the study. Each of them expressed their written consent to participate in the examination and signed the consent form before the study. During the procedures, the rules of Good Clinical Practice were applied and the Helsinki Declaration was followed. Criterion for inclusion was a click sound that appeared at the end of the abduction and was not diagnosed as an RDC / TMD diagnosis. The exclusion criteria were: trismus, patients who do not agree to participate in the study, non-cooperative patients during the study, patients with active herpes and patients with systemic sclerosis.

The temporomandibular disorders were classified with the use of the RDC/TMD (24) . The right and left sides of the body were considered separately. The Polish version of the RDC/TMD questionnaire (translated by Osiewicz) was used (25) (26) . Two axes of RDC/TMD were used. Axis I was filled by the dentist and the axis II were filled by patients. After examination with RDC/TMD axis I and axis II every participant were auscultated with the two electronic stethoscopes Littmann 3200 from the right and left body side at the same moment. Devices convert analogue to digital domain signal with 4000 Hz sampling frequency. It makes it possible to reproduce harmonics sound components up to 2 kHz. Then the auscultatory signal is modified by three implemented filters to emphasize selected section of the band, simulating standard bell and diaphragm (since they are known and common in clinical practice of pneumatic stethoscopes usage) and additional extended mode. The bell mode amplifies sounds from 20Hz - 1 kHz but with higher gain between 20 – 200 Hz, diaphragm mode allows to use the full bandwidth (20Hz - 2kHz) with the part of 100 to 500 Hz emphasized. Extended mode works similarly but, in this case, the range between 50 and 500hz is favoured. The maximal amplification available in Littmann 3200 is 24x with 9 levels of regulation. In all the operating modes ambient noise reduction feature is enabled. User can modify settings using small graphical display and buttons. Stethoscopes are battery powered and provide power saving features. To obtain acquired signals, the device can be connected with computer via Bluetooth wireless interface. Dedicated application allows to create local patients database, graphically represent signals and also export them in the sound format. In the course of the carried out research, this feature has been used to prepare collected signals for further processing. The stethoscopes are approved for use in Poland, notification no. 0065 5244 2581, supplement no. 1836 4103 1912. Assessment of acoustical symptoms was performed on the basis of two acoustical bio-signals that were measured using electronic stethoscopes for about 15 seconds during which the patient kept on opening and closing the mouth.. Auscultation was carried out by applying the tip of the stethoscope to the facial skin in the preauricular areas, before the scrap of the ear to right and left

simultaneously. After that, the signals from electronic stethoscopes were sent to the computer to analyze the recorded signals.

Python 3 programming language was used for TMJ sound processing. The signal preprocessing consisted of [-1,1] amplitude normalization and removal of the DC component. In the next step the representation of the signal in the frequency domain was computed with the use of the Numpy library and Fast Fourier Transform algorithm. Nevertheless according to the papers cited in the Introduction section, the global signal spectrum is not an efficient method of analysis of non-stationary signals. Therefore we provided STFT of representative sounds calculated with the Matplotlib library. In order to split the signal into atomic sections for local spectral analysis, the Blackman window function of 512 samples length and 256 samples window overlapping was used. Spectrograms were presented in the linear time and frequency scale while the magnitude of each component was represented in the logarithmic scale. The frequencies below 80Hz were removed from spectrograms to emphasize higher harmonics that are responsible for the effect of clicking. They are however persisted for global spectral representation of each signal.

## Results

In the study group there were 47 people, including 29 women and 18 men. The mean age of participants was 32,46 years. The results of RDC/TMD diagnosis is shown in Table 1.

**Table 1 RDC/TMD axis I diagnosis in examined group of total 47 patients**

RDC/TMD axis I group diagnoses	Participants	Fraction
I- muscle disorders;	7	14.89%
II- disk displacements;	15	31.91%
III- arthralgia, osteoarthritis;	11	23.40%
Total with RDC/TMD axis I diagnoses	20	42.55%
Total without axis I RDC/TMD diagnoses	27	57.45%

From the whole group only 2 people fits the inclusion criteria. Two people from examined group had temporomandibular joint hypermobility. The first person with joint hypermobility was a woman at the age of 27. In a medical history, the patient noticed that he had been orthodontically treated in the past and now has a 33-43 tooth retainer. The clinical examination showed the dental arches without wisdom teeth and without 14, 24. Teeth 14 and 24 were removed due to orthodontic treatment. The relation of Angle's Class II and Class I canine relationship. The midline deviation was 1 mm to the right. Teeth 16, 17, 26, 27, 37, 36, 35, 34, 45, 46, 47 contain composite fillings. At a patient teeth wear were observed. It occurs in teeth 32-42, 11-21 and was measured by Smith and Knight tooth wear index(27). The result was 1 score. In Axis I RDC / TMD the patient reported no facial pain on both sides of the face. Opening pattern was straight in a clinical trial. The vertical range of motion was measured using the 11 incisor opening without muscle and joint pain was 40mm, the maximum active opening was 44mm and there were no muscle and joint pain complaints. The maximum passive opening was 48mm and there was no pain. Incisal relationship: horizontal 4mm, vertical 3mm. Opening movements were without muscle and facial pain: right and left lateral 13mm, protrusion 4mm. In examination followed with instruction RDC/TMD there were no noises during open, close, lateral and protrusive movements. Muscles and temporomandibular joint pain with palpation were not reported. In axis II, the questions about the general health and oral health was assessed by the patient as good. The patient felt no pain in the face, ear or temple. The female noticed a problem with sounds in both joints created during wide opening and while eating hard food or yawning. Sounds from both joints during wide opening were the reason of report for an examination. In the examination with RDC/TMD the result was without diagnosis. The last step was clinical examination with electronic stethoscope and the signals were sent to the computer for further analyze.

The second patient was a man at the age of 22. The reason of examination was sounds from TMJ during wide opening and closing and fear of abnormalities in the patients opinion. The patient is under dentist control. In a medical history, no orthodontic treatment in the past and currently only conservative treatment- fillings. The clinical examination showed the dental arches with the probability of agenesis of tooth 25 and 45. The relation of Angle's Class was I and Class II canine on the right and on the left Class I canine relationship. The patient had a midline that was correct, with no deviations from the norm. Teeth 18, 17, 16, 24, 27, 28, 36 contain composite fillings. In Axis I RDC / TMD the patient reported facial pain especially muscles and joint pain on both sides of the face. The patient described pain intensity as strong as 3 in the scale 0-3 were 3 is the most painful. Opening pattern was straight in a clinical trial. The vertical range of motion was measured using the 11 incisor opening without muscle and joint pain was 56mm, the maximum active opening was 63mm with pain located in the muscles on both sides of face. The maximum passive opening was 65mm, with pain in the muscles both sides. Incisal relationship: horizontal 4mm, vertical 2mm. Opening movements were without muscle and facial pain: right lateral 13mm, left lateral 14mm, protrusion 8mm. During protrusion movement patient noticed pain in the area of right muscle and joint with intensity of 3. In examination followed with instruction RDC/TMD there were no noises during open, close, lateral and protrusive movements. Muscles and temporomandibular

joint pain with palpation were reported- masseter with intensity of 2 on both sides and lateral pole of TMJ on both sides with intensity of 3. In axis II, the question about the general health was assessed by the patient as very good and oral health as good. The patient felt pain in the face, ear or temple in the last month. The male noticed a problem with sounds in both joints created during wide opening and while eating hard food, yawning, swallowing and ringing in ears. In the examination with RDC/TMD the diagnosis was Ia- myofascial pain and IIIa arthralgia. At the end the examination patient was auscultate with electronic stethoscope.

Both patients have hypermobility of the joints, which was confirmed by a functional x-ray of the temporomandibular joints, where it shows condyloma translation.

Recorded signals were collected and analyzed using algorithms implemented in the Python 3 language. The software provides graphical representation of the acquired sounds, which is an important functionality. Thanks to such a graphical representation, the person analyzing records can spot the differences between particular cases and also provide an information about their morphology from the signal processing point of view and further development.

On the basis of the Fig. 2 it can be easily assessed how the quality of the registered signal depends on the proper placing and contact of the stethoscope's head with the skin surface. When the downforce is too high or a grip is uncertain during the examination, uncontrolled movements of the stethoscope are possible. This in turn leads to friction, which may manifest as high amplitude ripples in time representation. On the other hand, the tension of diaphragm and tissues can significantly influence acoustic properties of the system. On the right part of the Fig. 2. higher frequencies of the spectrum are reduced in comparison to signal with no artifacts on the left. This proves that artefacts appearing during measurement results in changes of bandwidth which in turn might contribute to deceptive diagnosis.

In general, joints auscultatory signals feature noise-like spectral characteristics with amplified regions corresponding to joint movements during examination. Therefore each signal contains very low frequency component resulting from cyclic repetition of motoric activity. On the other hand, pathological clickings are caused by rapid dislocations of joint structures which is accompanied by the formation of considerable acoustical waves. One of the steps of the proposed processing methodology consists in DC removal. However asymmetrical sharp peaks are still visible in the signal time representation (Fig.3.). This phenomenon corresponds to the rapid stimulation of the stethoscope's membrane by click vibrations. Spectrum of the TMJH sounds is situated in the lower part of the frequency band and the amplitudes of its components are lower in comparison with pathological records.

In the Fig.4 there is presented original hypermobile TMJ sound with visible double peaks waveform, which is typical for TMJH. Another observation is that the amplitudes of vibrations corresponding to the joint movement between extreme positions are very low. This is in line with the anatomy and physiology of the joints. Movement of TMJ structures of healthy person is smooth and soundless according to the traditional auscultation criteria.

As it was already stated, analysis of non-stationary signals requires observation of frequency changes as a function of time, which can be achieved by the application of the time-frequency representation (spectrogram). As a result, characteristic frequencies can be differentiated in each section of recorded joint movement. Nonetheless artefacts present in the acquired sounds introduce heterogeneity and therefore can overlap diagnostic-valuable parts (Fig.5).

Hypermobility of TMJ can be easily distinguished from pathological clicking using spectrogram (Fig. 6). TMJH can be characterized by periods of quiet in recordings whilst cracks and noise are present (with different amplitude) during the whole record of sound of TMJ diagnosed with clickings. A second typical feature of TMJH is represented by double vertical bars corresponding to the hypermobile clicks, which does not occur in pathological signals.

## Discussion

Daily activities such as eating of hard foods, gasping, yawning in case of patients with hypermobility of the temporomandibular joints are associated with a specific sound described as thud (6). Sounds in the joints created during everyday activities performed by patients draw the attention of others, which is usually embarrassing. Ashamed patients focus their attention on repetitive loud sounds. This is often the reason why patients try to find help and treatment. In the standard RDC / TMD classification, there is no diagnosis for people who have sound (referred to as thud) in the final phase of the mandibular abduction movement (25) (26) (24). As current research shows signals from the temporomandibular joints can also be physiologically connected with the anatomy as in the participants with TMJH. It is necessary to take care of that group of patients and to give the right diagnosis. However, there has been published, an extended version of the RDC / TMD questionnaire, which includes a brief diagnosis of "Hypermobility Disorders". The name of the questionnaire is Diagnostic Criteria for Temporomandibular Disorders (28). Nevertheless only further clinical examination and additional medical investigation, for example with an X-ray, ultrasound or MRI can confirm the diagnosis. It should be stressed that in the proposed methodology the common stethoscope was used as the main measuring device. The stethoscope is very popular, cheap and also well-known medical equipment, easy to use and non-invasive. With the help of an electronic stethoscope and numerical data, it is easy to distinguish a graphical representation (e.g. spectrogram), which is associated with the sounds of TMJH patients. Also other researchers e.g. Nosouhian et. al. noticed the difference in auscultation in the group of patients with severe GJH and TMJH (29). Many advantages of using a stethoscope for the purposes of confirming the TMJ diagnosis can be pointed out. First, auscultation with a stethoscope is a part of an examination that can be performed during a patient's visit in the consulting room and immediately analysed in order to visualize the measured signal on the computer screen. Measured acoustical signal and its representation in the frequency and time domain are characteristic for each sound-related dysfunctions in TMJ. Moreover a stethoscope can be used in certain cases when the x-rays are contraindicated (e.g. in case of pregnant women). In the course of the carried out research, all the recorded and analyzed signals were acquired using the same equipment. On one hand, this seems to be a proper approach since the signals are comparable, but on the other, signals are subjected to the same artefacts. Errors are inevitably related

to the construction of the stethoscope itself. Among the most common problems we can distinguish significant influence of transfer function / amplification frequency characteristic on resonance phenomena or attenuation of a significant part of the band. To verify the quality of the acquisition setup, further analysis with advanced equipment and repeatable measurement conditions is required. Nevertheless it should be stressed that possibility of application of the proposed methods in clinical conditions forces the usage of commercially available and certified medical devices - not sophisticated laboratory equipment that is difficult to operate.

TMJ dysfunctions are manifested through incorrect disc displacement during movement. The whole mechanism is very complex and all the essential components such as the mandibular condyle, temporal bone, articular disc, joint capsule, ligaments, blood vessels and nerve supply are involved in the joint movement.

Changes in the TMJ internal structure result in the acoustical symptoms such as clicking, crepiting or thud sound during the joint movement. Therefore nowadays, one of the commonly used TMJ examination methods is auscultation by stethoscope. It is a popular technique in which the obtained results depend a lot on the experience of the medical personnel and the normalized properties of the devices. Auscultation could farther play an important role in the examination, diagnosis and future treatment of temporomandibular disorders. However the abnormal noise generated during joint movement could be nowadays evaluated by normalized and objective methods, which could eliminate disadvantages of the classical approach and could be used at the different stages of the joint disorders providing correct diagnosis.

Development of such simple and efficient methods should be treated as a challenge due to the wide spectrum and types of sounds (coming out) from degenerated joints resulting from many primary functional and anatomical reasons. However, in this paper, such a methodology has been proposed. Based on that, an examination of the joint and recording of noises has been carried out during the ordinary, free movement of the joint, which ensured repeatable condition of the movement. The investigation could be conducted in all accessible ranges of the movement. As a scope of investigation the functionality of the whole mechanism is considered, which is a great difference and advantage in the comparison with e.g. medical imaging methods that provide information concerning geometrical properties of the joint or the internal bone structure only. Medical imaging methods do not provide the sufficient information concerning the influence of tissues of lower density: muscles, ligaments not to mention synovial fluid or phenomena occurring in microscale on moving surfaces such as the grease layer, local Hertz stress, etc. Such methods have limited applications in the TMJ diagnostics due to the fact that the measurement of geometry is performed in the static state (no motion). At the same time, spatial resolution of medical imaging methods makes it impossible to measure structural changes of bones or joint surfaces of the size of which is smaller than the resolution of used equipment.

Important feature of the method proposed in the paper is that acquisition of the acoustical signals throughout the examination of the joint takes place during the functional activity of the joint. Such

conditions allow to measure and then analyse the influence of all the sources of joint dysfunctions such as degeneration of joint surfaces and synovial fluid or excessive muscles tension. This primary sources of dysfunction appear jointly and influence the reciprocal movements and rearrangement of tissues in the proximity of the joint.

Analysis of acoustical signals of THJ activity carried out in the frequency-time domain by the use of short time Fourier Transform algorithm has allowed for visualization of the generated sounds and decomposing them into time and frequency components. On the basis of the obtained results of STFT analysis, hypermobility of TMJ can be easily distinguished from pathological clicking. It is worth to emphasize that such an analysis could be performed immediately during the patient examination. Therefore methods of auscultation can be complemented with the biomechanical observation of the movement of joint and analysis of accompanying signals displayed in the form of spectrograms in the linear time and frequency scale and the magnitude of each component expressed in logarithmic scale.

The acoustical disturbances of the recorded signals are removed by filtering the frequencies below 80 Hz in order to purify and emphasize more significant higher harmonics corresponding to the acoustical effect of clicking. The examination process is comfortable for both patients and doctors. The signals collected with the electronic stethoscope Littmann 3200 are recorded and sent to the computer via the Bluetooth connection without the necessity of establishing any wire connection or manually prompting signal processing since the whole analysis is performed automatically and the results are immediately displayed.

## Conclusion

Based on our research, we note that hypermobile joints are rare case among patients. In our study group, only 4% has sounds like thund. Due to the uncommon occurrence of such patients, research should be conducted to look for TMJH and spread them so that the results of the research can expand the knowledge of dentists.

The comparative analysis of disorders mentioned in this paper proved that hypermobility can be distinguished from other dysfunctions based on the characteristic time frequency features present in the spectrogram representation of TMJ sound.

We recorded and analyzed sounds from the temporomandibular joints of patients with TMJH. However, due to the small number of TMJH patients it was not possible to create a reference database of these sounds. Unfortunately, the goal has not been achieved yet, but we plan to continue further research.

Additional analysis of signals from Littmann 3200 can become easily in the future including more advanced diagnosis with electronic equipment. The kind of sound and characterization of them is helpful in diagnosis. Cooperation with medical and technical research can improve and become easier to understand the character of the sound by using computer technology.

# Abbreviations

TMJ- temporomandibular joint

TMD- temporomandibular disorders

FEM- Finite Element Method

MDA- Multi-body Dynamics Analysis

TMJH- hypermobile temporomandibular joint movement

GJH- generalized joint hypermobility

RDC/TMD- Research Diagnostic Criteria for Temporomandibular Disorders

STFT- Short-Time Fourier Transform

RID- Reduced Interference Distribution

NN- Nearest Neighbour

NCLC - Nearest Constrained Linear Combination

ZSS - Zero subspace

STIR - Scale and Time-shift Invariant Representation

TIR- Time-shift Invariant Representation

RGK - Radially Gaussian Kernels

MEMS - Microelectromechanical systems

FPGA - Field Programmable Gate Array

# Declarations

## Availability of data and materials

All data and documents are maintain by Jagiellonian University in Cracow, Poland

## Consent for publication

Not applicable

## Competing interests

"The authors declare that they have no competing interests"

## Authors' contributions

JL was a responsible to approval by the Bioethics Committee, patient signatures agreed, patient's examination: interview, auscultation, diagnoses, major contributor in writing the manuscript

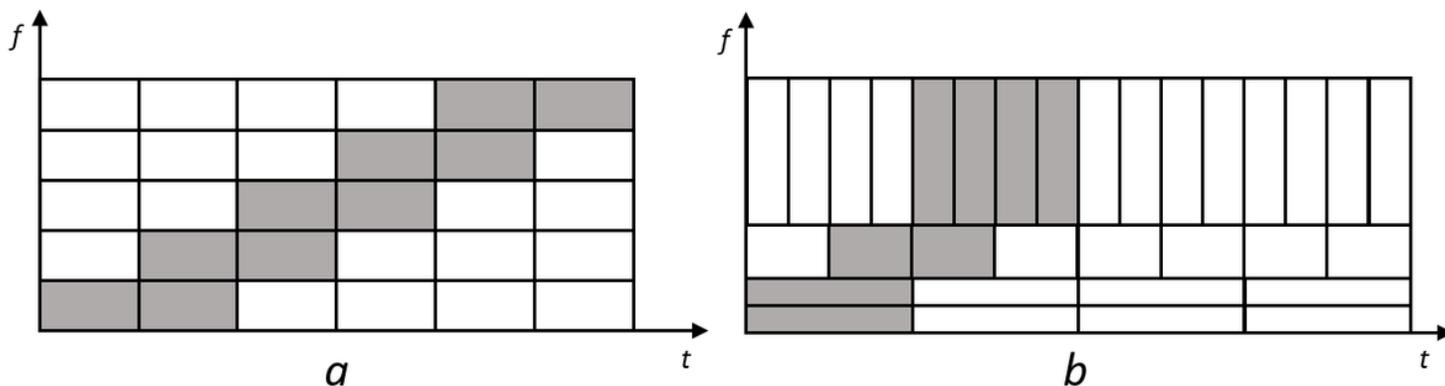
JE.L medical expertise, editing, DG technical expertise, signals analysis, MK signals analysis, algorithms preparation and was a major contributor in writing the manuscript MI signals analysis, JI validation. All authors read and approved the final manuscript.

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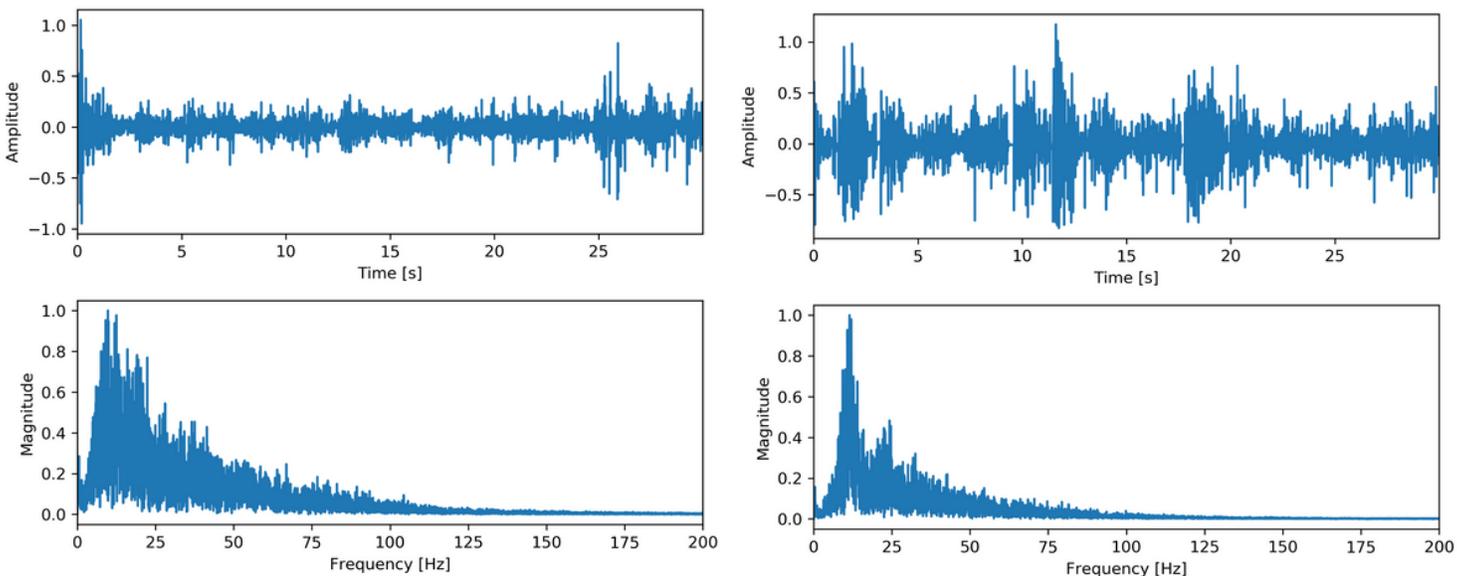
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## Figures



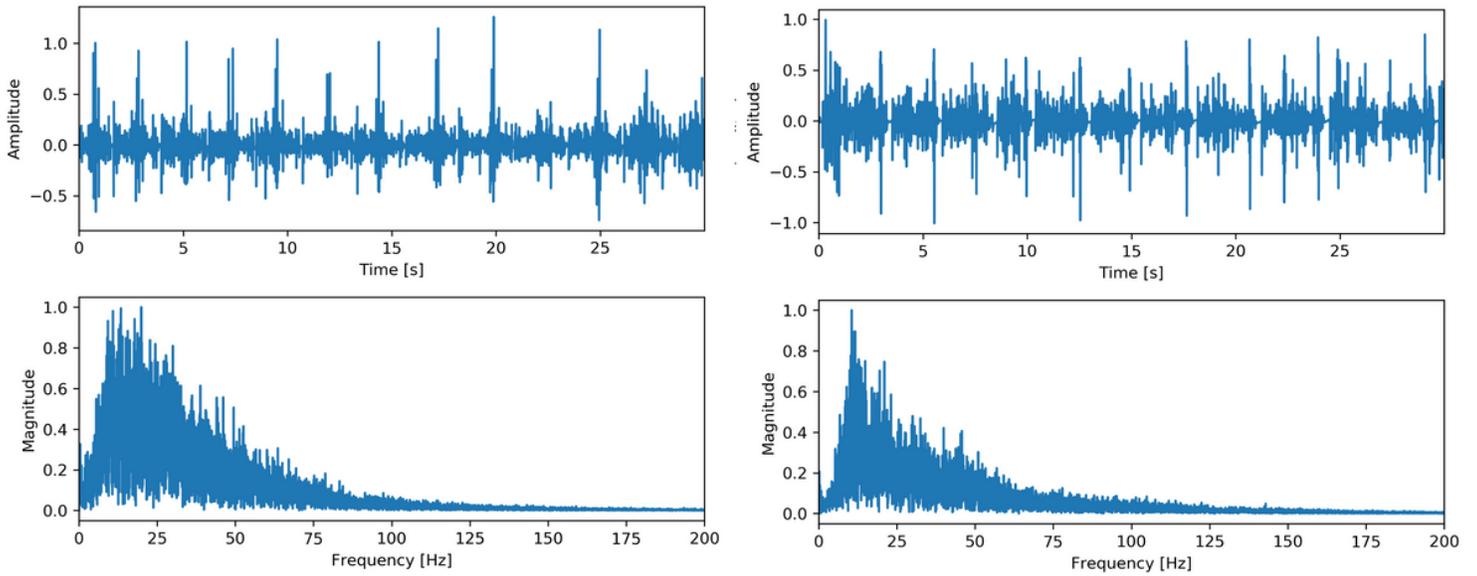
**Figure 1**

Exemplary basic time-frequency decomposition chessboards: a) STFT, b) Wavelet Transform of a signal with linearly increasing frequency. Grey cells represent non-zero decomposition coefficients.



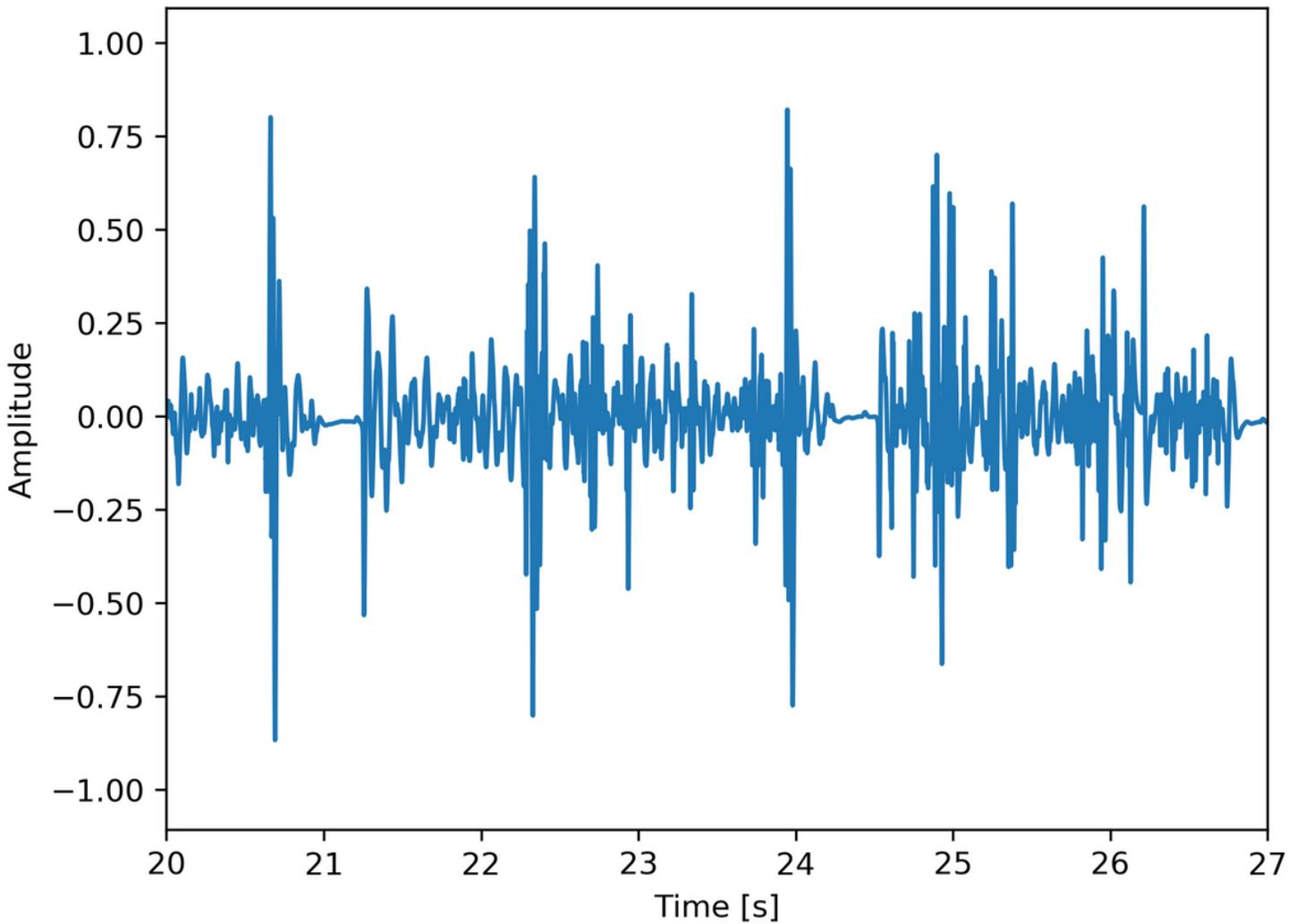
**Figure 2**

Acoustical signals of the patient with no TMD syndroms in time and frequency domain. Graphs on the left show sound of health TMJ, on the right side we can observe artefacts caused by the incorrect contact of the stethoscope diaphragm with patient's skin.



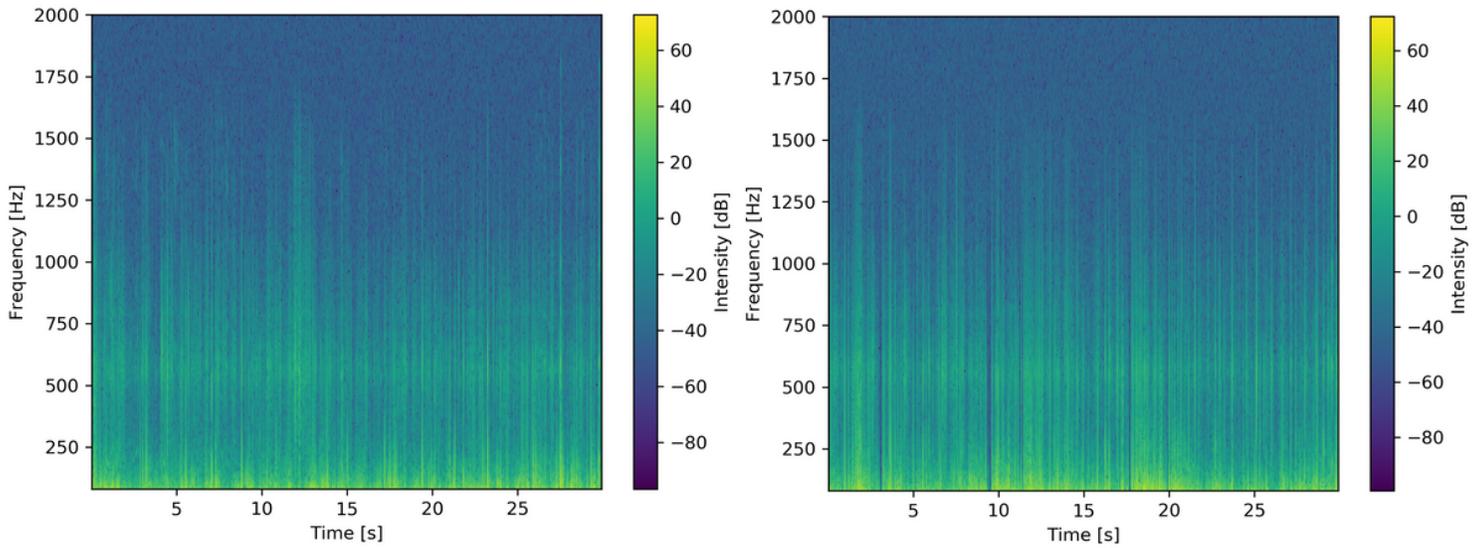
**Figure 3**

Comparison of pathological (on the left) and healthy but hypermobile (on the right) TMJ sounds in time and frequency domain.



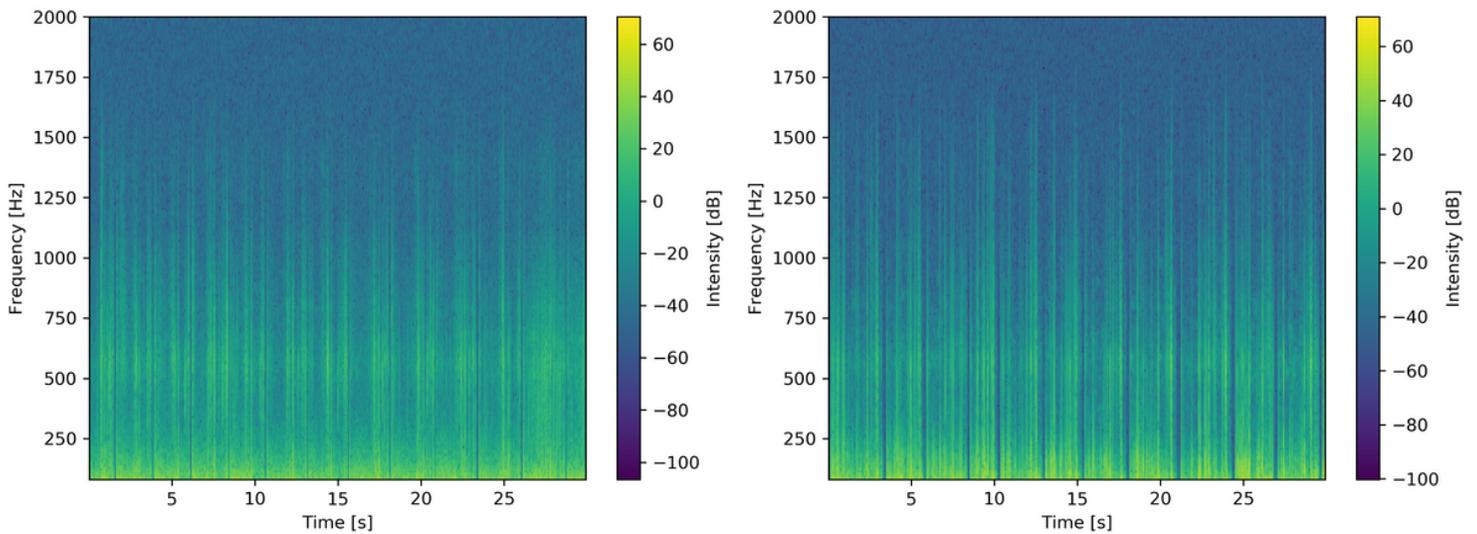
**Figure 4**

Sample of hypermobility auscultation signal in time domain



**Figure 5**

Spectrograms obtained for patients: healthy and healthy with artefact. Left graph shows sound of the healthy TMJ, on the right side we can observe artefact caused by incorrect contact of diaphragm with patient's skin.



**Figure 6**

Comparison of spectrograms estimated for the patient with pathological clicks of TMJ (left side) and the patient with TMJH (right side).