A Vibration Sensor Approach to Detect Intra-Articular Needle Tip Placement in the Knee Joint

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Research Article

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Abstract

Background: Intra-articular injection in the dry knee joint is technically challenging particularly for the beginners. The aim of this study was to investigate the possible use of the vibration sensor to detect if the needle tip was at the knee intra-articular position by characterizing the frequency component of the vibration signal during empty syringe air injection.

Methods: Two milliliters of air were injected supero-laterally at extra- and intra-articular positions of a cadaveric knee joint, using needles of size 18, 21 and 24 gauge. Ultrasonography was used to confirm the positions of needle tip. A piezoelectric accelerometer was mounted medially on the knee joint to collect the vibration signals which were analyzed to characterize the frequency components of the signals during injections.

Results: The vibration frequency band power in the range of 500-1,500 Hertz was visually observed to potentially localize the needle tip placement during air injection whether they were at the knee extra-articular or intra-articular positions, as demonstrated by the higher band power (over -40 decibel or dB) for all the needle sizes. The differences of frequency band power between extra- and intra-articular positions were 18.1 dB, 26.4 dB and 39.2 dB for the needle size 18, 21 and 24 gauge respectively. The most obvious difference was found in the smallest needle diameter.

Conclusions: A vibration sensor approach was preliminarily proved to distinguish the intra-articular from extra-articular needle placement in the knee joint. This study demonstrated a possible alternative electronic device implementation of this technique to detect the intra-articular knee injection.

Background

Intra-articular knee injection is a common procedure in treatment and diagnosis of the knee joint. For example, local anesthesia injection to the knee joint is done in the elective knee arthroscopy cases [1, 2] and in some knee physical examinations that need to be done under anesthesia [3], gadolinium contrast media injection in knee joint imaging [4] and viscosupplement and corticosteroid injection to alleviate the knee pain. These procedures are done as the knee osteoarthritis is one of the most common degenerative joint disease and impacts functional capacity in elderly (prevalence of 3.8% and 2.7 times more common in women than men) [5]. Disease pathophysiology of knee osteoarthritis involves inflammatory process of synovium and structural changes of articular cartilage including subchondral bone [6]. Most of the patients suffer from pain, stiffness and impaired joint mobility and often require intra-articular injection with non-steroidal anti-inflammatory drug, corticosteroid or viscosupplement agent for pain relief and inflammation control to improve joint function.

The accuracy of intra-articular needle placement is a vital key to prevent soft tissue complication and achieve a good treatment outcome by avoiding inadequate analgesia and agent concentration in the intra-articular space. To minimize potential complications of extra-articular injection from local tissue damage, such as atrophy of muscle and subcutaneous fat, pain, skin hypo-pigmentation [7] and skin necrosis [8], proper placement of needle is advocated to confirm intra-articular needle position [9]. Many injection techniques with different knee postures are proposed to use for agents delivery to the knee, however the best portal and posture is still controversial [10]. A systematic review demonstrates the superolateral approach in extended knee has the best accuracy around 91% compared to other approaches in the similar posture (lateral mid-patellar 85%, anteromedial 72% and anterolateral 67%) [11]. However, in 90^{o}-bended knee position, a study using squishing technique [12] and post-injection mini air-arthrography [13] showed higher accuracy (89%) of modified anterolateral approach compared to superolateral approach (58%) [14].

No matter what techniques used, the accuracy of needle tip placement needs to be enhanced, particularly when the knee effusion is not present or the symptomatic dry joint [15]. The position of needle tip can usually be detected whether it is extra- or intra-articular by ultrasonography. The ultrasound-guided knee injection and aspiration offers greater accuracy and clinical improvement over using only the conventional landmark technique [16–19], however, the imaging technique requires extra time and the cost of machine could make it not available in the limited-resource settings. When the ultrasound machine is not available, the tactile sensation can be used to distinguish the positions. Absence of the backflow when the needle tip in intra-articular, detecting from the tactile feedback felt at the syringe, has also been proposed [20] and implemented as an instrument [21] for the imaging-free technique to increase the intra-articular injection accuracy. However, it takes a steeper learning curve to do so particularly without an assisted device.

A vibration sensor approach has been used in previous studies to detect the interested particle flow in the fluidized bed reactor. A fluidized bed reactor, used in many industrial applications, is a device that carries inside the multiphase chemical reactions. Vibration signals, usually taken from the piezoelectric accelerometer mounting outside the fluidized bed reactor, can be used to non-invasively detect the interested particle flow by characterizing the vibration frequency components, for example, to distinguish sand-oil-water flow from sand-water flow [22] and to detect the sand flow in the gas-sand flow [23] by observing the power spectral density for particular frequency bands of the vibration signals. The piezoelectric accelerometer, a surface contact sensor that converts the vibration signal in the form of acceleration of the piezoelectric material inside, assuming simultaneous moving with the attached surface, to the electrical analog signal that can usually be collected by an analog-to-digital system. After transforming those vibration signals into the time-frequency domain commonly by the short-time Fourier transform (STFT) and the wavelet transform [24], different patterns corresponding to the different flow phases, e.g. with or without solid particles in the flow, can be observed and characterized.

When different multiphase flows can be classified using the vibration frequency analysis, detection of injected air flow through different anatomical structures should also be a possible application. It was then hypothesized that the flow of air injection originated from the needle tip at different anatomical locations can be distinguished using vibration frequency analysis, suggesting the needle tip placement either intra- or extra-articular positions. The aim of this study was therefore to compare the vibration signals of intra-articular and extra-articular air injection into the cadaveric knee using the piezoelectric accelerometer sensors, in order to characterize the frequency power band of the detected vibration signal.

Methods

Experimental setup

One fresh male cadaver, which was preserved at 4 degree Celsius for 48 hours after death, was set up for bilateral knee injections at room temperature via superolateral approach using a 10-milliliter centric tip Nipro luer lock syringe (SY3-xLC-EC) and 1.5-inch (38-millimetre) thin wall needles of gauge size 18G (HN-1838ET), 21G (HN-2138-ET) and 24G (HN-2438-ET), Nipro needles, 3-9-3, Honjo-Nishi, Kita-ku, Osaka, Japan. A surface-contacting piezoelectric accelerometer sensor (352C33, PCB Piezotronics, USA) was mounted at medial compartment of the knee (just below medial border of patella) firmly to obtain skin to sensor surface contact (Fig. 1). Ultrasonographic linear probe was used to confirm position of needle tip either extra-articular or intra-articular part (Fig. 1). Two milliliters of the air were injected from the empty syringe in both extra-articular (quadriceps tendon) and intra-articular locations, then the vibration signals generated in the knee joint were collected through the sensor (see *Acquisition of the vibration signals* for details).

Ultrasonographic confirmation of the needle tip positions

The ultrasonographic linear transducer was placed over the quadriceps tendon and visualized to check for anatomical landmarks of the knee joint. Needle tip position either extra-articular or intra-articular position was ultrasonographically confirmed by a skillful musculoskeletal radiologist, using Siemens S3000 ultrasonography machine and linear probe (14L5) with a frequency between 5.0 and 14.0 MHz. The two milliliters of air were injected superolaterally as fast as possible into the quadriceps tendons (extra-articular knee injection) during ultrasonographic visualization (Fig. 2A). The same volume of air was injected at the similar location but deeper into the intra-articular space (beneath quadriceps tendon and above articular cartilage of lateral femoral condyle) under ultrasonographic confirmation (Fig. 2B). The vibration signals were recorded via the sensor which was mounted medially at the knee joint.

Acquisition of the vibration signals

The vibration signals were collected from the piezoelectric accelerometer (352C33, PCB Piezotronics, USA). The signal was sampled at 10,000 Hertz (Hz) through an analog-to-digital converter (DEWE-43-A, 24-bit resolution with anti-aliasing filter), connecting to a computer laptop with the data acquisition software (Dewesoft X) to record the data (Fig. 3). The sensitivity of accelerometer was 102.9 millivolt/gravitational acceleration (mV/g). The vibration signals were recorded in the unit of gravitational acceleration (g) for 3 seconds. No other filter was applied to the signals.

Signal processing and parameters calculation

The vibration signals were analyzed in time-frequency domain. The short-time Fourier transform was applied to the signal in order to visualize the power spectral density of the signal as time progressing, i.e. the spectrogram. Interested frequency band was determined by visual inspection. Quantification of the frequency band power was done by calculating the summation of the spectral power of the signals in the interested frequency bands after the discrete Fourier transform (256 samples per segmentation with the Hamming window of 250 samples and the overlap of 256 samples) of the signals.

Results

Time frequency response

The time-frequency responses are displayed in the spectrogram shown in Fig. 4. Higher power spectral density at the high frequency band (approximately 500–1500 Hz) was observed when the needle tips were in the knee intra-articular position (bottom row), but not in the extra-articular position (top row). The phenomenon was seen in all needles sizes (A-C), even though the clearest was seen in needle size 24G (Fig. 4C).

Spectral power

Summation of power spectral density over the interested frequency band (frequency band power) was used to quantify the spectral power. Figure 5 showed the summation of power spectral density in the low (50–500 Hz) and high (500-1,500 Hz) frequency bands. In the low frequency band, the spectral power was quite high, approximately over − 40 decibel (dB) (in dark red color), and hard to distinguish between the extra-articular or intra-articular needle tip locations (Fig. 5A). When the needle was intra-articular, higher power spectral density of the high frequency band was observed, unlike the case of the extra-articular needle position (Fig. 5B). The difference of power spectral density was 18.1 dB, 26.4 dB and 39.2 dB for the needle size 18G, 21G and 24G respectively.

Discussion

Because the dry knee joint is more difficult to find proper needle position before agent injection than the effused one which synovial fluid helps confirm intra-articular needle placement, the experiment then simulated in fresh cadaveric study with dry knee joints to represent real clinical setting. We have preliminary tested if the vibration sensor, i.e. a piezoelectric accelerometer, can be used to enhance the accuracy of needle tip placement by distinguishing the vibration signal when the needle tip was at the extra-articular and intra-articular positions of the knee joint during the hard-push empty air injection. Usually, the needle position from the air-pushing is detected by audible squishing sounds or feedback tactile sensation at the syringe and confirmed by ultrasonography as done in the present study.

The result has shown that when the air injection was at intra-articular site, high power spectral density of approximately over − 40 dB was present particularly in the high frequency band (500–1500 Hz), compared with the low frequency band (50–500 Hz) as seen in Fig. 5. For the case of extra-articular positions, high spectral powers were mainly observed in the low frequency band. This phenomenon was seen in all needle sizes. Intra-articular air flow injection detected from an accelerometer placed at the medial compartment of the knee can therefore be characterized as the higher power spectral density (over – 40 dB) in the frequency band of 500–1500 Hz.

Characterizing the vibration signals from the air injection in the knee joint can be similar to the case of vibration monitoring in the fluidized bed. The frequency components of vibration signals developed from the presence of air flow is commonly observed in the phase flow in the fluidized bed. For example, large bubbles usually correspond to low frequency signals found of the be [24]. Likewise, in the present preliminary study, when the needle tip was at extra-articular position, the air flow in the quadriceps tendon that might fluctuate the peri-articular tissue could contribute to the power of low frequency components. Air flow velocity, bubble formation and bubble size also reflect in the power of vibration signal. When the air flow is present in the fluidized bed, sharp peak of the power spectrum at 1,000 Hz is found regardless of the flow velocity. But when the air velocity is increasing, higher frequency components gradually appear between 3,600-4,000 Hz. When the frequency components in the range of 800-1,500 Hz appears, it is the sign of bubble formation. Vibration frequency components can refer to these regimes of particle flow [24]. Therefore, high frequency component observed when the needle tip is at intra-articular location during empty syringe air injection is possible, in which the present study found the frequency component in the range of 500–1500 Hz.

However, needle sizes may affect the power spectral density of the vibration signal. With the similar volume flow rate, the needle with larger diameter can cause more fluctuation to the peri-articular tissues as in the case of the 18-gauge needle, where the power spectral density in the high frequency band in the extra-articular case was higher than other needle sizes (Fig. 5B). For the case of intra-articular 24-gauge needle air injection, smaller cross-sectional flow causing faster flow velocity could also affect higher spectral power (Fig. 5B). Further study with more samples is recommended to increase test reliability.

Conclusions

The superolateral empty syringe air injection technique with a vibration sensor was preliminarily proved to distinguish the intra-articular from extra-articular needle placement in the knee joint. This vibration sensor approach could be a possible technique to detect the accurate location of needle placement. This study demonstrated the possible electronic device implementation of this technique to detect the intra-articular injection when ultrasound machine is not available.

Declarations

- Consent for publication

Not applicable

- Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

- Competing interests

The authors have no competing interests. No benefit(s) in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.

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- Authors' contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Rit Apinyankul, Kritsada Siriwattanasit and Witchaporn Witayakom. The first draft of the manuscript was written by Rit Apinyankul and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Ethics approval and informed consent

The study protocol was reviewed by the institute's Ethics Committee for Human Research, and deemed exempt from the institutional review board oversight because the study met the criteria of the Exemption Determination Regulations (research involving the collection of study of bone, the body of persons who donate to the university hospital and subjects cannot be identified directly or through identifiers linked to the subjects). Informed consent was also waived as the cadaver was donated to the university hospital and was anonymous. This was approved by chairman of panel 1 Khon Kaen University Ethics Committee in Human Research and the study was carried out in accordance with guidelines of Khon Kaen University.

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Figures

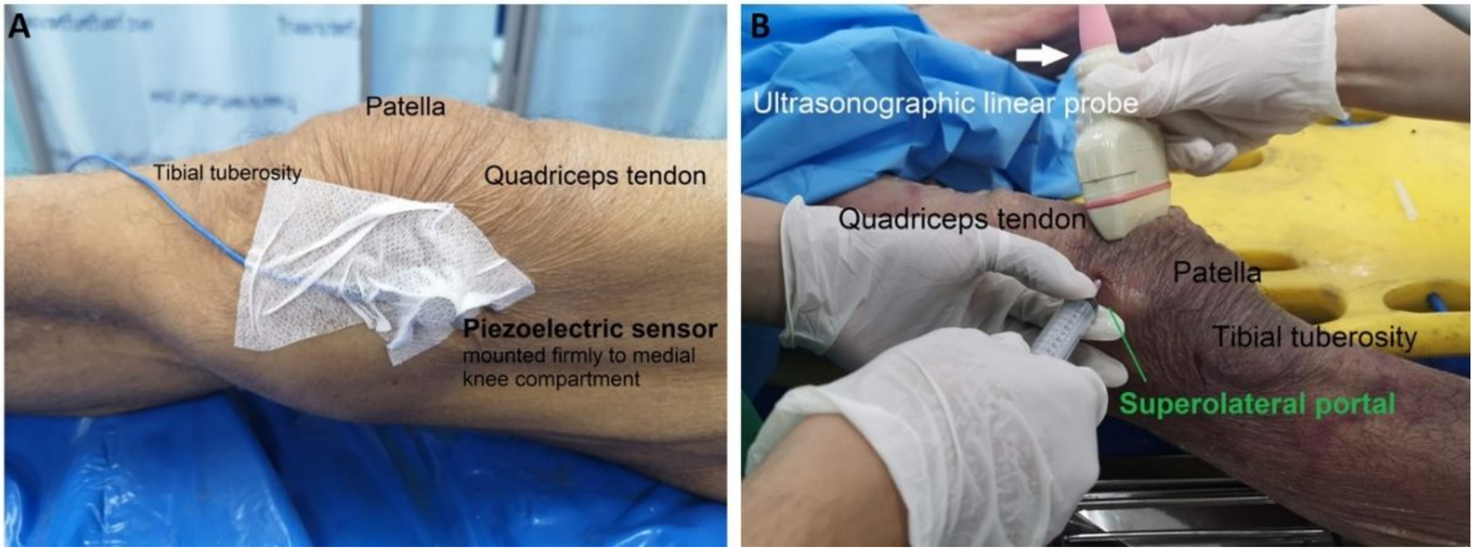

Figure 1

Experimental setup was done by mounting the accelerometer firmly at just below medial border of patella (A). An empty syringe was placed at supero-lateral knee, ready for the 2-milliliter air injection, and a linear ultrasound probe was positioned on the quadriceps tendon over the patella (B).

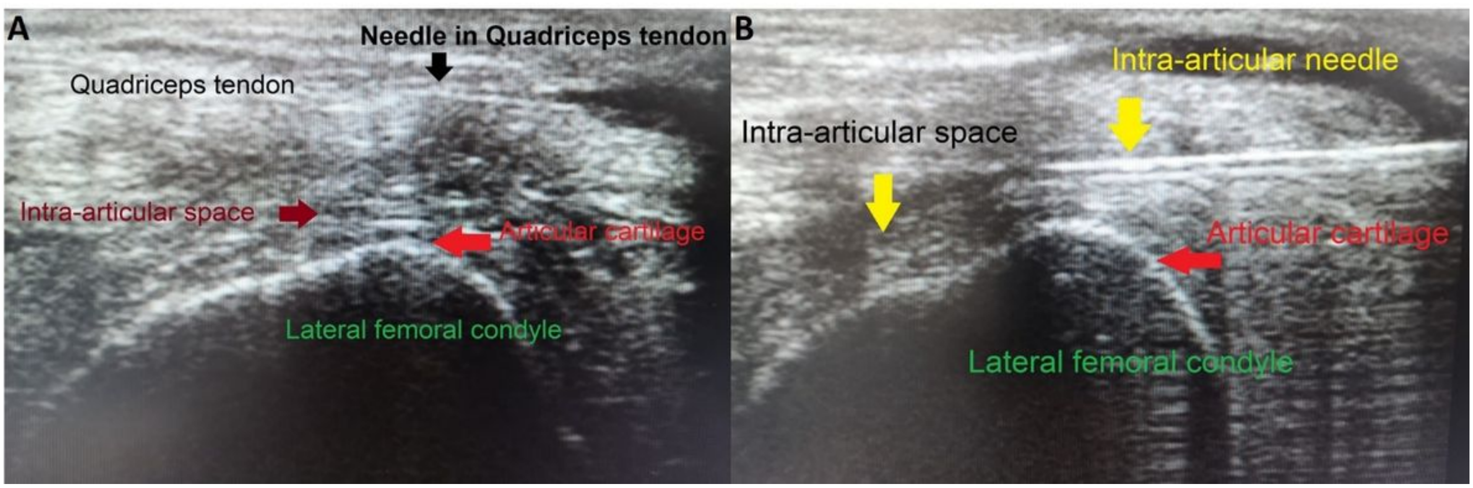

Figure 2

Ultrasonographic visualization of the articular knee and the needle tip to confirm extra-articular (A) and intra-articular (B) positions. Extra-articular position was defined as the needle tip was at the quadriceps tendon. For intra-articular injection, the needle tip position was in the intra-articular space beneath the quadriceps tendon and above the articular cartilage of lateral femoral condyle.

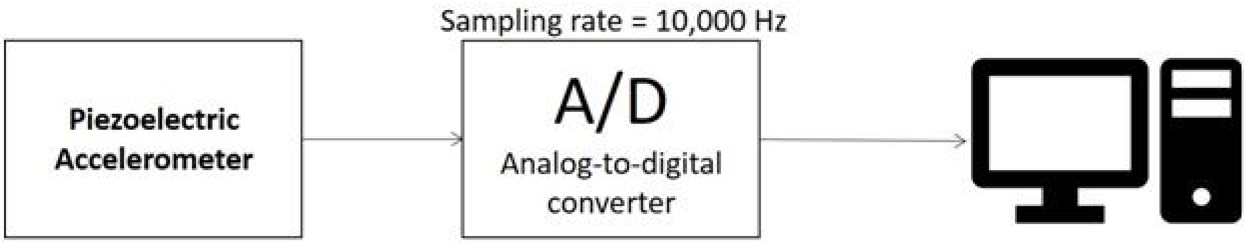

Figure 3

Schematic diagram of the vibration signal acquisition system. The system consisted of a piezoelectric accelerometer, an analog-to-digital converter with sampling rate of 10,000 Hertz (Hz) and a computer to collect and display the signals.

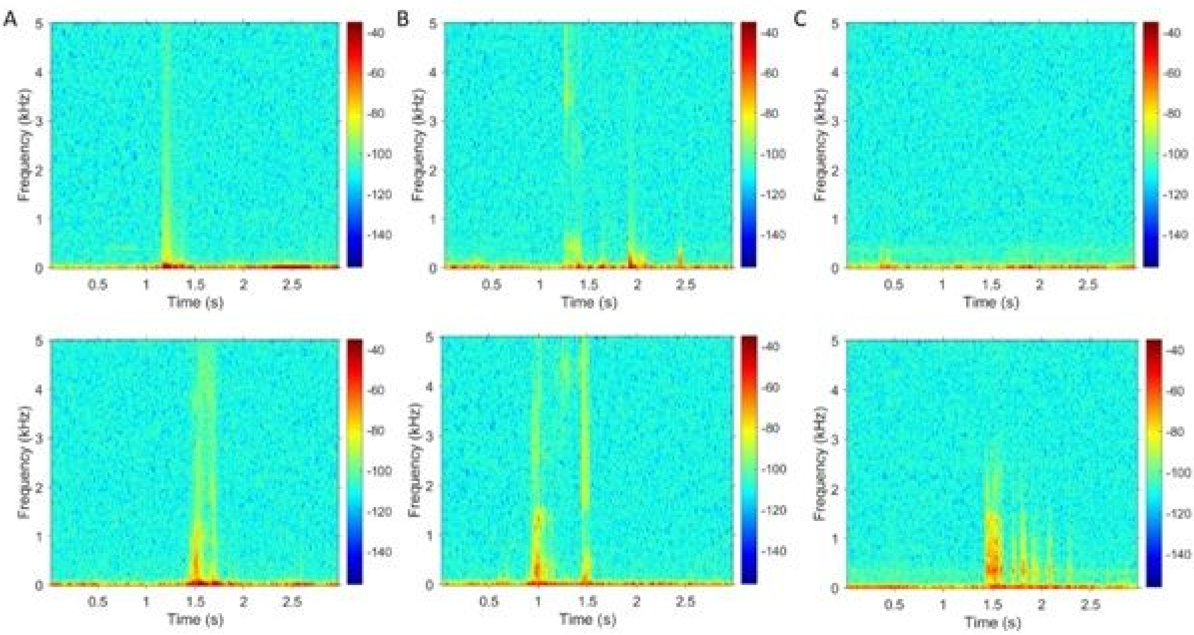

Figure 4

Spectrogram of the vibration signal illustrated frequency (kilohertz or kHz) and time in second (Time(s)) when the injection was done at the extra-articular (top row) and intra-articular (bottom row) knee joint for the needle size of 18 (A), 21 (B) and 24 (C) gauge.

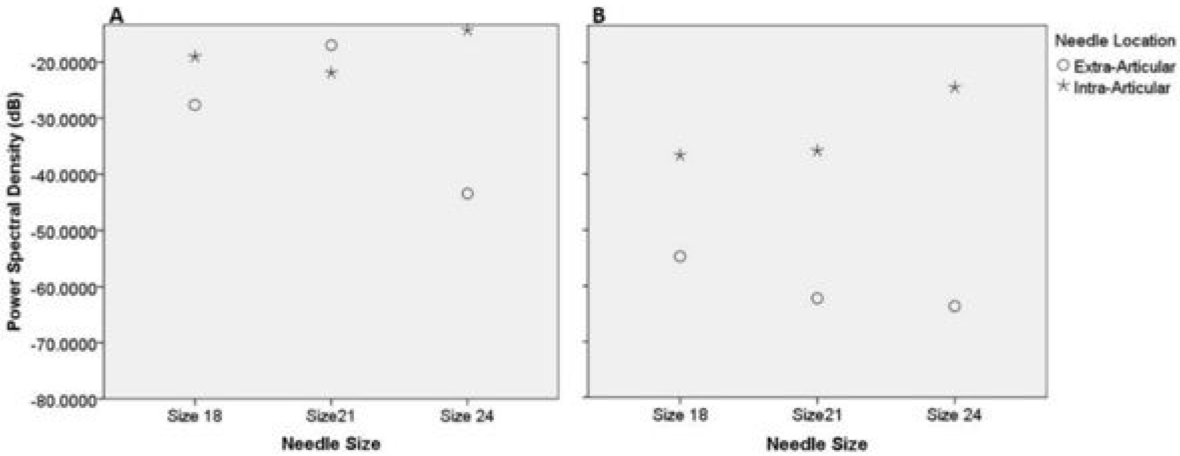

Figure 5

Power spectral density in decibel (dB) of the A. low (50-500 Hertz) and B. high (500-1500 Hertz) frequency bands for needle size 18, 21 and 24, in the case when the needle tips were either at the extra-articular (round markers) or intra-articular (star markers) locations.