Detection of Hip Dysplasia in Infants Using Audible-Frequency Acoustic Transmission Measurements

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***Abstract*— Developmental hip dysplasia (DDH) is present in 0.2-0.3% of human newborns. Diagnosis may be made by skilled physical examination, or more commonly by utilizing hip ultrasound imaging. The latter is limited by availability, cost and skill, especially in low resource setting and in the developing nations. A low-cost, easy to use and sensitive DDH screening method would be helpful to assist with early detection, facilitating early and more effective intervention and thereby minimize chronic disability. The current study investigated the utility of an acoustic screening method for DDH. The primary hypothesis is that audible sound transmission through the hip joint is affected by DDH and that these transmission changes are detectable. The method was tested in a clinical setting using a compact system. This involves inputting a brief acoustic signal at one location and measuring the transmitted signal at another. Two different transmission configurations were tested. A decrease in acoustic transmission at certain frequencies was appreciated in DDH patients at the affected side with sensitivity of 80% and specificity of 50-79% depending on the exciter location. The higher accuracy was achieved when the excitation was performed at the anterior superior iliac spine and the transmitted signal was measured at the trochanter. Soothing the infants (e.g., using a feeding bottle, a pacifier, etc.) significantly helped in avoiding crying and movement artifacts that can interfere with the method.**

Keywords—Developmental dysplasia of the hip, acoustic, spectral analysis.

I. Introduction

Developmental dysplasia of the hip (DDH) in infants is common with approximately 2-3 per thousand children suffering from this condition [1]. Early intervention in affected children is widely believed to lead to decreased rate of late presentation [2], while delayed detection may cause less effective treatment resulting in chronic disability in this population. Current screening methods in infants include certain physical examination techniques (e.g., the Ortolani and Barlow maneuvers), but these require significant skill and training to perform reliably. Ultrasonography can be used as a screening tool, but its utility is limited by unavailability in low resource settings, cost, and reliance on highly trained professionals [3, 4]. Therefore, it would be useful to develop new non-invasive, easy to use, low cost, and accurate tools for DDH screening by primary care providers and for developing regions.

Sound transmission in the human body can be affected by the tissue composition along the sound path and the surrounding structures. Therefore, for pathologies involving structural changes, acoustic transmission may correlate with certain medical conditions. Previous studies suggested that sound transmission measurements may be used to detect a variety of pulmonary, gastrointestinal, vascular, and cardiac conditions [5-10].

Developmental dysplasia of the hip will likely involve noticeable anatomical changes that may affect sound transmission through the hip joint, and hence may lead to detectable sound transmission changes. These changes involve differences in bone contact areas at the hip joint. Previous studies suggested the utility of sound transmission for the detection of hip joint changes. For example, an earlier study [11] used sound attenuation of a 256-Hz tuning-fork to diagnose DDH. That study used a tuning-fork placed on the patella and acquired transmitted sound with a stethoscope over the lower abdomen. In all of 56 observations made on 18 children with congenital dislocation of the hip, a unilateral reduction of sound transmission was noted in 53 tests. The study also found that when a normal hip was flexed, transmitted sounds decreased or remained the same.

Kwong et al. [12] tested a sound excitation system that generated pink noise (at the sacrum) using a shaker (Bruel & Kjaer, Type 5961, with a mild force of vibration of <0.7 N rms) to detect transmission in normal neonates and in those with unilateral DDH. Results showed that the coherence of sound transmitted through the hips was high (0.89-0.96) for preschoolers, neonates and adults. The highest coherence was found in the adult group, whereas the lowest coherence was found in the preschool group. The neonate's coherence was slightly lower than the adults in that study. A second study [13], used the same technique and found a significant difference between the normal neonates and patients with unilateral DDH. A "discrepancy parameter" was calculated and a discrepancy cut-off achieved a sensitivity of 100% in detecting DDH. Frequencies that were most effective were around 200, 250, and 315 Hz.

Kapicioglu et al. [14] used an electroacoustic exciter with a range of 20Hz to 20 kHz and two microphones to differentiate between normal and abnormal hips. The study reported that dysplastic hips had lower sound transmission values than normal hips in a study of 22 patients (average age 5.9 years; range 0.3-14 years). Four patient positions were tested in that study: a) hips and knees neutrally positioned and measurements performed between the patella and the pubis symphysis, b) hips and knees neutrally positioned and measurements performed between the patella and the anterior superior iliac spine (ASIS), c) hips and knees positioned at 45 degree and 90 degree of flexion, respectively, and measurements performed between the patella and pubis symphysis, and d) hips and knees positioned at 45 degree and 90 degree of flexion, respectively, and measurements performed between the patella and the ASIS. In each position, the sound exciter was placed on the patella and the receiver was applied on the pubis symphysis and ASIS. That study showed that sound transmission in dysplastic hips were lower than normal hips for flexed hips with no clear trend reported in extended hips. Hip flexion increased transmission in normal hips more than DDH hips. Results also showed that sound transmission decreased with age. The frequency range used was broad and a narrow frequency range was not clearly reported.

Based on reviewing previous studies, it can be concluded that (a) the measurement systems utilized and the results varied significantly among studies. (b) accurate quantification of acoustic transmission in the body requires robust (i.e., with high signal to noise ratio) systems for sound generation and detection. (c) sound transmission in infants and young children is not well studied. (d) more studies are needed to investigate the utility of audible sound transmission measurements for DDH detection, especially in young subjects.

In the current study, an acoustic system for DDH screening in infants was built and tested. Screening young children is important since early detection is associated with better outcomes. The current system is meant to be compact, low - cost, wireless, and suitable for low resource clinical settings. The system relies on quantifying the acoustic transmission through the hip joint, which may be affected by DDH. The primary hypothesis is that hip dysplasia causes detectable changes in audible frequency acoustic transmission.

II. Methods

A. Hardware, Data Acquision and Analysis

The proposed device (Figure 1) is designed to measure sound transmission characteristics through the bones and joints in infants. This is achieved by inputting an acoustic signal at a chosen skin surface location (i.e., excitation point) and measuring the transmitted signal at another surface location (i.e., receiving point). The nature and frequency content of the acoustic signal needs to be chosen with care to allow optimal investigation of sound transmission. Factors affecting the choice of excitation signals include: causing minimal disturbance to the study subjects and containing relatively wide range of frequencies. The excitation signal was generated using a computer to have high flexibility in signal design [15]. This signal contained band limited white noise in the 50-1000 Hz range to allow the investigation of sound transmission at frequencies that proved useful in previous studies [10-14]. The signal amplitude was set to about 70 dB when measured in the ambient air 20 cm away from the excitation point. This moderately loud sound signal was chosen over a chirp (which is consists of a sweeping pure tone) to avoid disturbing the study subjects.

Figure 1. The compact device constructed and tested in the current study. It is housed in a carrying case and consists of a Bluetooth digital player [P], a Bluetooth bone conduction exciter [E], two wireless stethoscopes [S_R, S_L, for the right and left patient sides], two cell phones [C_R and C_L, for the right and left sides], and a power charger [R]. The medical-grade double-sided tape [T] is also included in the case.

The generated excitation signal was uploaded to a digital player (Model: Q3E, Timmkoo, China), which sent it via Bluetooth to a bone conduction exciter (Model: Humbird, DuraMOBI, China), which is most efficient in the 120Hz-16kHz. The speaker was secured to the subject skin at the excitation point using a medical grade double-sided tape (B-205, 3M, Maplewood, MN). Two Bluetooth stethoscopes (Stemoscope, San Diego, CA) were secured to skin at the receiving points using the same tape (B-205, 3M, Maplewood, MN). The stethoscopes wirelessly sent the measured sounds to a Stemoscope Android app running on the cell phones. The app recorded the sound in the phone memory in ".wav" format, then the phone uploaded these sound files to Google Drive.

B. Signal Analysis

The sound files were download from Google Drive to a laptop computer for signal analysis. The digital signal processing software code was written using Matlab (R2022b, Mathworks, Natick, MA). Signal processing included calculating the power spectra (using the "pwelsh" function) of excitation and transmitted signals and the transfer function (using the "tfestimate" function) between the two transmitted signals. Matlab calculates the transfer function of two signals (e.g., x, and y) as the ratio between the cross spectrum of the two

signals (P_{xy}) divided by the power spectrum of the first signal (P_{xx}).

C. Experimental Protocol

After IRB approval, 56 infants with either normal or unilateral DDH (37 Females, 9±8 weeks old, mean±SD, five patients had DDH with four on the left) participated in the study. After enrollment, subjects rested on an exam table in the supine position with their hips and knees flexed at approximately 90 degrees. To measure acoustic transmission, one exciter and two stethoscopes were used as shown in Figure 2. The two stethoscopes were placed at the greater trochanter (one at the right and another at the left). Two locations were considered for the exciter, the first was the pubis symphysis and the second was the anterior superior iliac spine (ASIS).

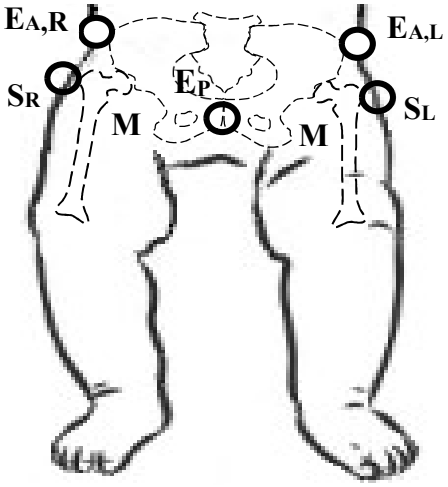

Figure 2. Experimental setup showing two configurations for the Exciter [E] and stethoscope [S] locations. In the first configuration the exciter [Ep] was at the pubis symphysis. In the second configuration, the exciter was either at the right ASIS [$E_{A,R}$] or left ASIS [$E_{A,L}$]. In both configurations, the stethoscopes were at the right and left trochanter [S_R and S_L]. There are muscles and soft tissue [M], that may have played a "bridging" role in sound transmission.

When excitation was performed at the pubis symphysis, the left and right stethoscope signals were recorded simultaneously. This configuration measures pubis to trochanter transmission and will be called "PT configuration". The ASIS to trochanter transmission was done one-side at a time and will be called "AT configuration".

III. Results and Discussion

Figure 3 shows a typical example of acoustic spectra for the excitation signal (i.e., exciter input) and transmitted signals (left and right stethoscope outputs) for a normal subject with the exciter placed at the pubis symphysis. It can be seen that the excitation signal contained uniform energy up to about 1000 Hz where the energy decreased gradually as the frequency increased above 1kHz. The spectra of the left and right stethoscope signals also showed gradually decreasing energy above 1000 Hz similar to the excitation signal, as expected. The left and right stethoscope signals showed spectral energy variations below 1000 Hz, which would be reflective of a frequency-dependent acoustic transmission.

Previous studies reported that acoustic transmission in soft tissue varies within this frequency range and is dependent on the tissue characteristics between the excitation and receiving locations [6]. The results of Figure 3 also shows that the spectra of the left and right stethoscopes were comparable. To quantify the left and right transmission differences, the transfer function between the left right signals was calculated and is shown Figure 4(a) for one patient. The transfer function values were within

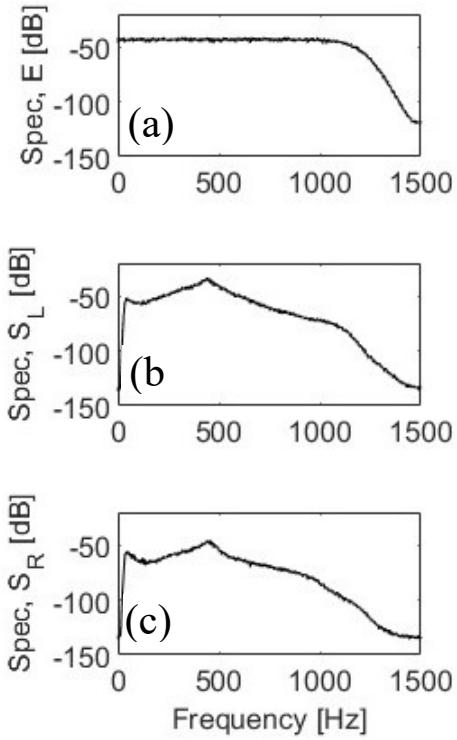

Figure 3. Example of the power spectral density (in one patient) of the (a) excitation signal, (b) left stethoscope and (c) right stethoscope. For a normal subject, left and right spectra were comparable.

±6 dB in the analysis range of interest (from 150 to 900 Hz) where the signal-to-noise ratio was high. The deviation of the transfer function from zero may be, at least in part, due to small left-to-right anatomical asymmetry [16] or small sensor placement errors. It is to be noted that the two stethoscopes used in the current study were tested using a sensor calibration system [15] and their sensor-to-sensor spectral differences were within ±3 dB, which is smaller than the differences seen in Figure 4(a) for normal hips.

Figure 4(b) shows the transfer function for one patient with unilateral left hip dysplasia. Here, the left-to-right transfer function showed a drop of about 14 dB. This drop is consistent with the decreased acoustic coupling between the femur head and the acetabulum due to the left DDH. The reduced transmission in this frequency range with compromised

acoustic coupling was reported in other studies [11-14]. The transmission drop was calculated for all patients in both the AT and PT experimental configurations and the patients with dysplasia tended to have a reduced in transfer function in the affected side. A threshold on the transfer function drop was used to separate normal and DDH patients for the AT and PT

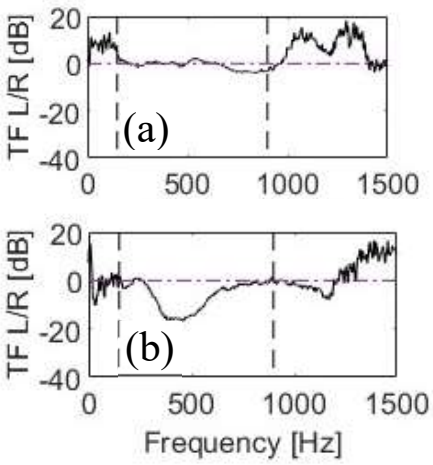

Figure 4. Example of the transfer function between left the right stethoscopes (in one patient) for (a) normal subject and (b) left DDH subject. There was a drop of energy transmitted to the left stethoscope (compared to the right) in the left DDH subject. The vertical dashed lines mark the range of analysis (150-900 Hz), where the signal-to-noise ratio was high.

configurations. The sensitivity was 80% (4 of 5 subjects) for both configurations, while the specificity was 50% (14 of 28 subjects) and 79% (22 of 28 subjects) for the PT and AT configurations respectively. However, the transfer function was not significantly different (p=0.06 and 0.34 for the PT and AT configurations, respectively) between normal and abnormal hips, which may be due to the relatively small number of subjects in the current study. A larger number of subjects is needed in future studies.

The sensitivity data suggests that the diagnostic accuracy depended on the exciter location, with the ASIS excitation providing higher accuracy over the pubis location. Although the exact reason for this is not known with certainty, this trend may be partially due to a better acoustic coupling to the ASIS and/or less soft tissue at that location. Another, possibly more important factor, is the presence of more soft tissue and muscles in the medial thigh (labeled M in Figure 2) that can provide an alternate route (in addition to transmission through the bones and hip joint) for wave propagation from the pubis symphysis to the trochanter. This parallel route may provide a bridging effect that compete with transmission though the hip joint, which would lead to less differentiation between normal and DDH in the proposed approach.

Study limitations

A primary limitation of the proposed screening method is the need for a relatively quiet environment during the brief time (15 to 30 seconds for each exciter configuration) of acoustic measurements. For example, loud continuous crying and baby movements generated noise louder than the excitation signal. Data from noisy subjects (about 23 recordings) were excluded from the study, which reduced the number of subjects from 56 enrolled subjects to 33 subjects with high quality recordings. At the beginning of the study, the number of subjects with this kind of loud noise was high (~80%). However, when soothing the baby by bottle feeding, using a pacifier, etc, the number of subjects with loud noise dropped to 10-15% towards the end of the study. In addition, noise removal techniques such as adaptive filtering may be utilized in future studies to reduce noise effects. Although comparable to some previous studies, the number of subjects participating in the study was relatively small, and therefore results has to be interpreted by care. Future studies will enroll more patients to further confirm the results of the current study.

IV. Conclusions

A method for screening infants suspected of DDH was proposed. A system for measuring acoustic propagation though infant hips was constructed and tested. The method involved gently inputting acoustic excitation at one skin location and detecting transmitted sounds at another location. Results suggested that that the accuracy of the proposed method depended on the location of the input. The sensitivity of the method was as high as 80%, while specificity ranged from 50 to 79 %. The higher accuracy was achieved when the acoustic excitation was performed at the ASIS and the transmitted signal was measured at the trochanter. Soothing infants by a feeding bottle, a pacified, ets., helped avoid the loud crying or motion artifact noise that interfered with the operation of the proposed measurement. More studies are needed to test this method in more subject.

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