Clin Orthop Relat Res (2008) 466:802–808
DOI 10.1007/s11999-008-0163-1

SYMPOSIUM: DEVELOPMENTAL DYSPLASIA OF THE HIP

Diagnosis of Developmental Dislocation of the Hip by Sonospectrography

M. I. Safa Kapicioglu MD, Feza Korkusuz MD

Published online: 15 February 2008

Abstract Because not all infants can be screened for DDH by experts, early diagnosis of developmental dysplasia of the hip (DDH) by primary health care professionals is important. We developed a broadband electroacoustic sound transmission-detection (sonospectrography) system and explored its utility in 22 patients (average age, 5.9 years; range, 0.3–14 years) with unilateral DDH in this preliminary study. Distinct from ultrasonography, the sonospectrography system functions by sound transmission and recording through tissues to differentiate between normal and abnormal hips. All hips were examined at four different hip and knee positions. The normal hip served as the control. The sonospectrography system was able to detect unilateral DDH. Dysplastic hips had lower sound transmission values when compared to normal hips in all patients and all four positions; however, the highest ($X = 88.8 \pm 30.2$ Hz) and lowest ($X = 8.3 \pm 5.4$ Hz) sound transmission mean values were obtained at different positions in the normal hips and those with DDH. Sound transmission values of dysplastic hips were always lower than that of normal hips when the hip and knee was flexed during measurements. Sound transmission values decreased with age. The sonospectrography system may offer a new noninvasive method in the diagnosis of unilateral DDH but requires further study of sensitivity and specificity of detecting dysplastic hips without subluxation in newborn infants.
Level of Evidence: Level IV, case series. See the Guidelines for Authors for a complete description of levels of evidence.

Each author certifies that he has no commercial associations (eg, consultancies, stock ownership, equity interest, patent/licensing arrangements, etc) that might pose a conflict of interest in connection with the submitted article.
Each author certifies that his institution does not require approval for the noninvasive sound transmission human protocol for this investigation and all investigations were conducted in conformity with ethical principles of research.

M. I. S. Kapicioglu (✉)
Department of Orthopedic Surgery and Traumatology, Faculty of Medicine, Selcuk University, Meram, 42080 Konya, Turkey
e-mail: safa.kapicioglu@gmail.com

F. Korkusuz
Department of Physical Education and Sports, and Medical Center, Middle East Technical University, Ankara 06531, Turkey
e-mail: feza@metu.edu.tr

Introduction

Diagnosis of developmental dysplasia of the hip (DDH) is crucial in fast-growing underdeveloped communities with the tradition of swaddling [11]. Early diagnosis of the disease relies mostly on physical examination by experienced health care professionals and ultrasound screening of the hip with proper probes. Primary care physicians working in rural places lack the knowledge on DDH examination [24] and the availability of an experienced health care professional certified for ultrasound screening is typically unavailable. Late onset of DDH is not rare [21] and screening should cover followup examinations until the child is walking [4]. A noninvasive, simple, and inexpensive device that can be used by inexperienced midwives, obstetricians, and primary care and family physicians in field practice and at periodic examinations for the screening of DDH would therefore be useful.

In vivo assessment of mechanical properties of bones [1, 20, 25] and joints [3, 9, 10, 12, 23] by vibration and sound propagation analysis is not new. Mollan et al. [18] and

McCoy et al. [16] described the advantages of the use of vibration sensors to detect acoustic signals passing through joints. Sensitivity and objectivity were the advantages of this non-invasive method. In 1987, Stone et al. [23] described a two-part clinical trial for diagnosing DDH based on the attenuation of sound transmission across the hip using a stethoscope and a 256-Hz medical tuning fork. However, they used only a single frequency sound generated by the medical tuning fork and a qualitative signal detection method. Chu et al. [3] used microphones to record sound transmission and later subtract the background noises in tissues. However, they did not evaluate sound transmission through joints. Kwong et al. [13] developed an acoustic device and examined 16 patients with unilateral DDH. Using the center of the sacrum for excitation of the vibration force they were able to record structural asymmetry between normal and dysplastic hips.

We describe a broadband electroacoustic generator combined with a receiver (microphone)—a so-called sonospectrography system entirely different than ultrasound. We then asked if sound transmission differs between normal and dysplastic hips by quantitative measurement at four knee and hip positions. Second, we asked which knee and hip position presents the largest difference of sound transmission between normal and dysplastic hips. Finally, we asked if sound transmission would diminish with age in normal and dysplastic hips.

Materials and Methods

We recruited 22 patients, 19 girls and 3 boys, with an average age of 5.9 ± 4.3 years (range, 0.3–14 years) radiographically diagnosed with unilaterally dislocated hips and examined each hip in all patients using sonospectrography. The normal hip served as the control for the dysplastic hip. We examined the hips in four positions and compared the amplitude of the signals at different frequencies. Information on the study was given and a written consent for participation in examination procedures and surgical and/or nonsurgical treatments was obtained from the patients' parents.

Both hips were examined in four positions: (1) Position 1 - Hips and knees were neutrally positioned and measurements were performed between the patella and the symphysis pubis (Fig. 1A). (2) Position 2 - Hips and knees were neutrally positioned and measurements were performed between the patella and the anterior superior iliac spine (ASIS) (Fig. 1B). (3) Position 3: Hips and knees were positioned at 45° and 90° of flexion, respectively, and measurements were taken between the patella and

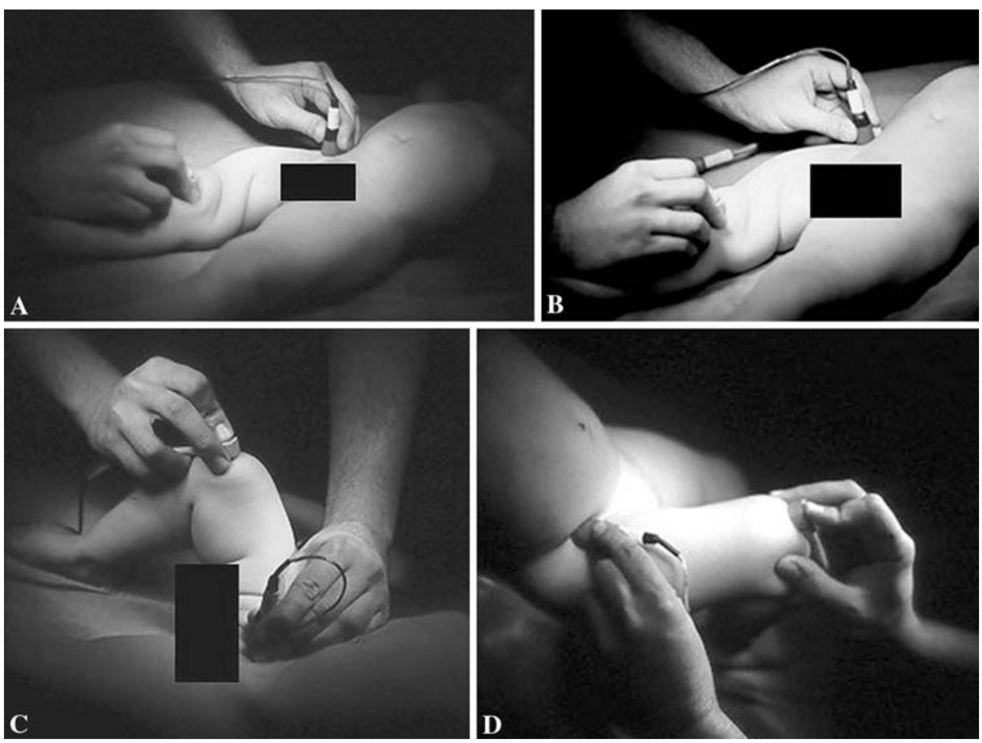

Fig. 1A–D (**A**) Position 1: Hips and knees were neutrally positioned and measurements were performed between the patella and the symphysis pubis. (**B**) Position 2: Hips and knees were neutrally positioned and measurements were performed between the patella and the anterior superior iliac spine (ASIS). (**C**) Position 3: Hips and knees were positioned at 45° and 90° of flexion, respectively, and measurements were performed between the patella and symphysis pubis. (**D**) Position 4: Hips and knees were positioned at 45° and 90° of flexion, respectively, and measurements were performed between the patella and the ASIS.

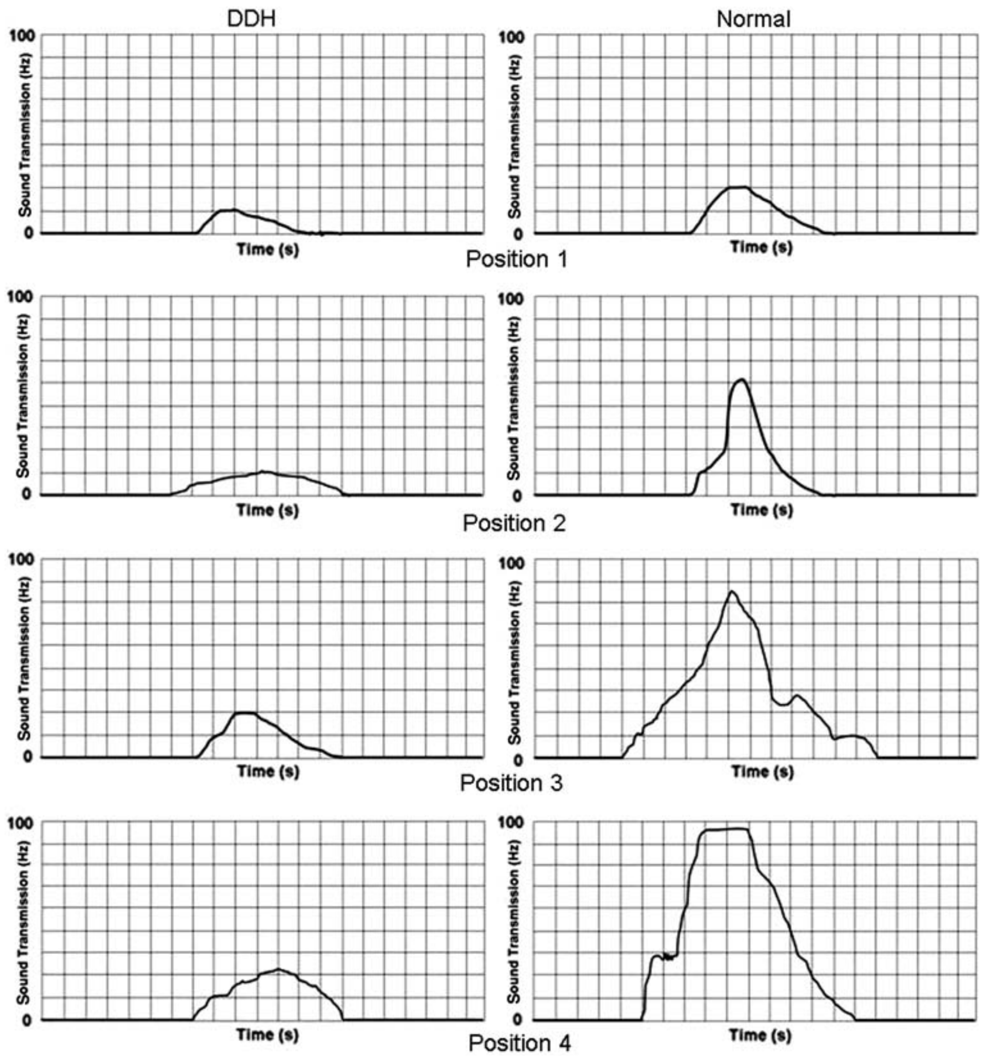

Fig. 2 Representative sonospectrographic measurement of the DDH and normal hip of a patient is pictured.

symphysis pubis (Fig. 1C). (4) Position 4: Hips and knees were positioned at 45° and 90° of flexion, respectively, and measurements were performed between the patella and the ASIS (Fig. 1D). Independent variables (n = 2) were the normal and dysplastic hips and dependent variables (n = 4) were the positions. In each position, the sound generator was placed on the patella and the receiver was applied on the symphysis pubis (positions 1 and 3) and ASIS (positions 2 and 4), respectively. We used differential amplitudes in a given frequency to compare the sound (Hz) between the dislocated and normal hips of the same patient (Fig. 2).

The broadband electroacoustic excitation system (sonospectrography) (Fig. 3) was an active system consisting of two main components: the sound generator and the microphone to quantify sound transmission through tissues. Sound generation and transmission components consist of an electroacoustic exciter in the 20 Hz to 20 KHz range, a driving amplifier, a frequency compensation system in order to produce flat-frequency excitation, and a linear ramp generator driving a voltage-controlled oscillator for automatic frequency scanning.

Fig. 3 The electroacoustic sonospectrography system is pictured.

The reception and recording channel consists of a broadband and sensitive semiconductor microphone, microphone preamplifier, and a sound energy computing integration system. The microphone is isolated for prevention of external noise by a special sound insulator. Received, measured, and computed sound data are recorded as a function of amplitude and frequency (spectrum) by two means of a two-channel analog recorder. Excitation and recording of sound was conducted at the 200 Hz to 2.5 KHz range throughout the experiments. The frequency scanning time for a complete sound spectrum measurement lasted about 3 seconds. The amplitude was expressed as percentage, as a function of frequency. The developed system was fully automatic allowing its use and application by unskilled healthcare professionals.

We performed paired t-tests to detect differences in signal amplitude between the dysplastic and normal hip sound transmission scores at the four positions. We then employed a one-way within subject analysis of variance (ANOVA) using Bonferroni posthoc testing for multiple comparison to determine differences between positions. Hotelling's trace value (5.097) was obtained using SPSS, v.11 (SPSS Inc, Chicago, IL), with significance value (0.000) in order to control reliability of results. We tested the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables was proportional to an identity matrix. The criteria used for this hypothesis was Greenhouse-Geisser with a value of 0.81 which was called as a test of sphericity. Finally, correlations were calculated between age and sound transmission scores. Throughout the analysis, significance level was set to equal 0.05.

Results

Normal hips always had ($p = 0.000$) higher sound transmission values than dysplastic hips at all measurement positions (Table 1). We observed the highest sound transmission amplitude difference between the dislocated and the normal hips at Position 4. This was followed by Positions 2, 3, and 1, respectively.

The highest ($X = 88.8 \pm 30.2$ Hz) and lowest ($X = 8.3 \pm 5.4$ Hz) sound transmission mean values were obtained at Position 4 in the normal hips and at Position 1 in the dysplastic hips, respectively (Table 2). Sound transmission values were higher in flexion than in the neutral position; this difference was more obvious in normal than in dislocated hips.

Sound transmission values decreased ($p < 0.05$) with age in all but Position 1 in both normal and dysplastic hips (Fig. 4). P values were 0.047, 0.034, and 0.004 for Positions 2, 3 and 4, respectively. We observed a negative correlation (Position 2: r2 = -%43; Position 3: -%45; Position 4: -%59) between age and transmission values in all, but not in Position 1 in normal and dislocated hips, indicating a decrease of value with age.

Table 1. Sound transmission (Hz) values of normal and dysplastic hips at four positions

Hip position	Normal hips (Mean ± StDev)	Dysplastic hips (Mean ± StDev)	Difference between normal and dysplastic hips (Mean ± StDev)	*p*
1	17.7 ± 10.4	8.3 ± 5.4	9.4 ± 6.9	0.000
2	34.7 ± 18.1	13.5 ± 9.7	20.1 ± 15.8	0.000
3	35.3 ± 21.9	13.2 ± 12.0	22.1 ± 15.2	0.000
4	88.8 ± 30.2	22.2 ± 11.5	66.6 ± 28.8	0.000

Table 2. Sound transmission value differences between the four knee and hip positions

Knee and hip position	Knee and hip positions compared	Sound transmission mean value difference (Hz)	p Value*
1	2	−11.5*	0.004
	3	−12.7*	0.022
	4	−57.2*	0.000
2	1	11.5*	0.004
	3	−1.3	1.000
	4	−45.7*	0.000
3	1	12.7*	0.022
	2	1.3	1.000
	4	−44.5*	0.000
4	1	57.2*	0.000
	2	45.7*	0.000
	3	44.5*	0.000

* The mean difference is significant at the .05 level.

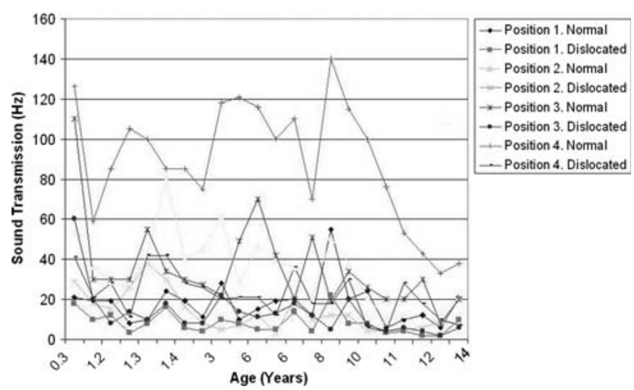

Fig. 4 Decrease in sound transmission value with age in normal and dysplastic hips is shown.

Discussion

The effectiveness of clinical and ultrasonic screening of DDH remains controversial [5] as late onset of the disease is not rare [21] and evidence is lacking either for [6] or against ultrasound screening [4, 27]. A sonospectrographic device was developed to noninvasively diagnose unilateral DDH at four different hip positions. The device, which is entirely different than ultrasound, is portable, inexpensive and easy to use at initial and/or followup examinations.

There are several limitations of our study. First of all, we view sonospectrography as an adjunctive quantifying system to supplement the physical examination; it has no superiority to ultrasound or radiographic examination in DDH screening. A surgeon should not manage a patient by using only this tool. However, the system can be used at the age of 4 months and older in unilateral DDH cases to augment physical examination findings. Further research is essential to predict its reliability and validity in newborn babies, as the youngest sonospectrographically measured patient in this study was four months old. In dislocated hips, however, we presume sound transmission values will be lesser even in newborn babies in the dysplastic side when compared to the normal side. We assessed validity of sonospectrography only in dislocated hips but not in subluxated or dysplastic hips. Although normal and dislocated hips of the same patients were evaluated in this study dislocated hips had substantially lower sound transmission values when compared to normal hips. We assume sonospectography can diagnose bilateral dislocated hips after a threshold between normal and dislocated hips for each sex and age will be set. Concentric closed reduction, however, cannot be ascertained with this device. Interobserver reliability was not measured; rather, we screened hips three times and used the highest sound transmission value. We did not evaluate gender difference due to the limited availability of unilateral DDH patients; however, as the structural deformity is obvious, we assume gender and age will not affect sonospectrography measurements extensively. Validity of the method was assessed only by radiographs but not by ultrasonography. Pre- and postoperative radiography and sonospectrography measurements were carried out longitudinally in one patient. One female patient with right total hip dislocation at 6 years of age was observed before, and 1.5 months and 3 months after, innominate osteotomy (Fig. 5A–C), and sound transmission values at identical time sections were recorded (Fig. 5D). Following surgery, sound transmission value increased in this patient on the dysplastic side. Interpretation of results in bilateral DDH patients can be difficult unless a normal and a pathological database of sonospectrographic measurements is established.

Sonospectographic measurements are simple, reliable and straightforward. There is no need for additional calculations and reporting after the measurements. Quantification of physical examination using sonospectrography is the advantage of this system. Further studies are essential to assess its effectiveness and reliability in comparison with ultrasonography. Our data suggest the sonospectrography system can detect DDH in patients between 4 months and 14 years of age. We observed three moderate and one intense resonance peak in all patients, which is similar to a typical vibration transmission pattern of the skeletal tissue. Of these four resonance peaks, the third and most intense resonance peak was recorded at about 410 Hz and the last between 600 Hz and 800 Hz. The last resonance peak was not detected in all cases. The sound transmission mean values were higher at Position 4 compared to other positions. Comparing sides in individual

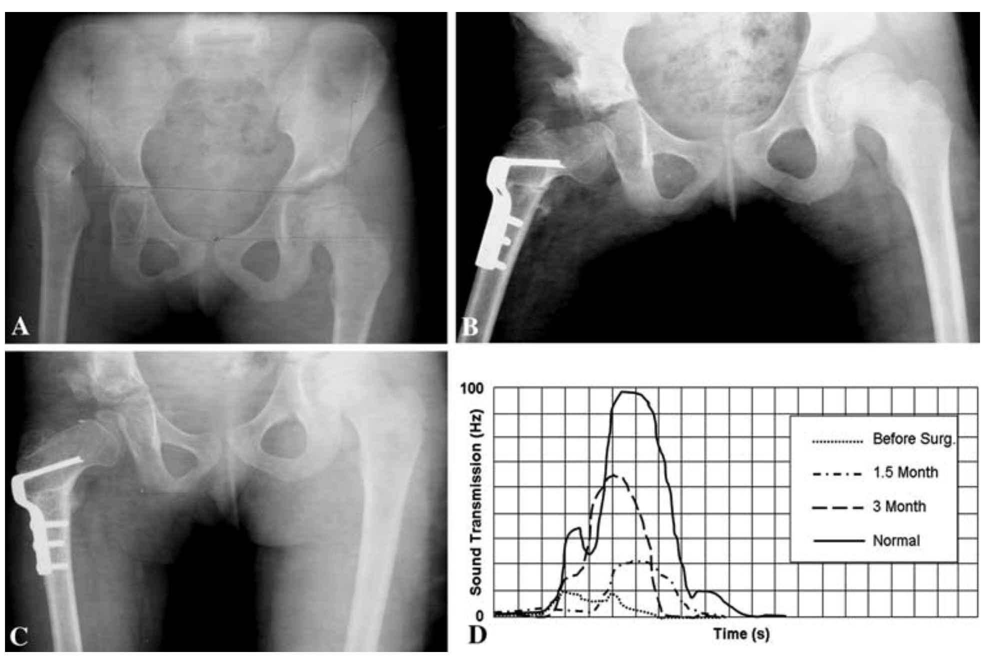

Fig. 5A–D Radiographs of a female patient with right total hip dislocation at 6 years of age (**A**) before, (**B**) 1.5 months, and (**C**) 3 months after innominate osteotomy, and (**D**) sound transmission values at identical time sections are presented.

patients, the highest amplitude difference between the normal hip and the DDH hip was observed at the same position. Although the number of measured patients was limited, measurement of the normal hip and the pathological DDH in the same patient increased the importance of the findings. Sound transmission values decreased as age increased. In older patients plain radiography can be used for diagnosis.

Our data suggest this novel electroacoustic sound excitation device—the sonospectrography system—effectively measured transmission and absorption spectrum of small amplitude sound waves in normal and DDH joints. Our device is distinct from that used in accelerometer studies [17, 18, 26] in that we did not measure or evaluate finite high-amplitude wave transmission using principles of nonlinear wave mechanics. Further, the sonospectrography system was built to be portable and to work with a battery.

We were able to effectively use the sonospectrography system to diagnose unilateral DDH in older children. Flexing the hip from neutral position caused an increase in amplitude recording. Early studies [22, 23] used similar techniques; these studies highlighted interobserver variability of the method and difficulty in screening bilateral DDH. Evaluations in these studies, however, were qualitative and subjective. We used acoustic waves received by the microphone and made and analyzed quantitative recordings. A commercially available mechanical vibration excitation device was used for the screening of unilateral DDH recently [12, 13]. In those experiments, the exciter and two microphones were separately placed on the posterior of the sacrum and over the greater trochanters, respectively. Measurements were furthermore made at the frequency range of 200 to 315 Hz. Acoustic vibration transmission measurements were made in single neutral hip positions in these studies. Our study differs from those studies by (1) exciting the hip at 4 different positions; (2) using the patella and ASIS for excitation and recording, respectively; and (3) generating sound at the 20 Hz to 2.5 KHz frequency range. The sonospectrography device developed and used in this study is a totally different device than the ultrasound that is used to screen the hip directly. In ultrasonic screening the sound wave is reflected from the musculoskeletal tissues constructing the hip. The sonospectrography device measures sound transmission through the tissues. In other words, transmission instead of reflection of sound from tissues is recorded in the later system.

The sonospectrography device is portable and can be used with battery power. Incidence of DDH will remain high in the future [2, 7, 8] and screening is essential until the child is walking [21]. The first step in the diagnosis of DDH from birth to about 6 weeks of age is physical examination [19]. Although Ortolani and Barlow tests have been used effectively as physical tests, the incidence of missed diagnoses of DDH has not decreased; on the contrary, it has increased in some centers [15, 19]. We, therefore, propose exploring the sonospectrography device for use in the field by primary healthcare professionals for the diagnosis of unilateral DDH. As sound transmission values of dysplastic hips are lower than normal hips, a database may be developed in the near future for normal and dysplastic hips to aid the early diagnosis of bilateral DDH as well. The sonospectrography device is inexpensive; developing the device can cost less than $5000.

For the purpose of diagnosis, the interpretation of sounds in the musculoskeletal system is relatively new. Vibration arthrography depends on the sounds elicited by moving joints, most often the knee and neonatal hip, and detected by surface transducers [11, 14, 17, 26]. Systems have been developed [12] and used [10] for the measurement of transmission properties of acoustic waves in the hip.

The sonospectrography system is a practical, novel, and noninvasive method that appears to reliably detect DDH in older children. Hip and knee flexion during sonospectrography examination increases wave propagation in normal and dislocated hips; the former being more obvious, and amplitudes decreased as age increased. We believe the system might be useful for screening newborns with dysplasia and without subluxation or dislocation, but reliability, sensitivity, and specificity will need to be established in these patients.

Acknowledgments We thank Professor Dr. Önder Tüzünalp and Alper Basaran of Ankara and Hacettepe Universities for their technical support during the development of the device and statistical tests, respectively.

References

1. Arpinar P, Simsek B, Sezgin OC, Birlik G, Korkusuz F. Correlation between mechanical vibration analysis and dual energy X-ray absorptiometry (DXA) in the measurement of in vivo human tibial bone strength. *Technol Health Care.* 2005;13:107–113.
2. Bennet GC. Screening for congenital dislocation of the hip. *J Bone Joint Surg Br.* 1992;74:643–644.
3. Chu F, Zhang D, Chai X, Qian X. A novel design of a portable otoacoustic emissions detecting system based on ARM. *Conf Proc IEEE Eng Med Biol Soc.* 2005;7:6758–6761.
4. Clarke NM, Clegg J, Al-Chalabi AN. Ultrasound screening of hips at risk for CDH: failure to reduce the incidence of late cases. *J Bone Joint Surg Br.* 1989;71:9–12.
5. Dezateux C, Rosendahl K. Developmental dysplasia of the hip. *Lancet.* 2007;369:1541–1552.
6. Graf R. Fundamentals of sonographic diagnosis of infant hip dysplasia. *J Pediatr Orthop.* 1984;4:735–740.
7. Green NE, Griffin PP. Hip dysplasia associated with abduction contracture of the contralateral hip. *J Bone Joint Surg Am.* 1982;64:1273–1281.
8. Kalamchi A, MacFarlane R 3rd. The Pavlik harness: results in patients over three months of age. *J Pediatr Orthop* 1982;2:3–8.

9. Kernohan WG, Beverland DE, McCoy GF, Shaw SN, Wallace RG, McCullagh GC, Mollan RA. The diagnostic potential of vibration arthrography. *Clin Orthop Relat Res.* 1986;210:106–112.
10. Kernohan WG, Trainor B, Nugent G, Walker P, Timoney M, Mollan R. Low-frequency vibration emitted from unstable hip in human neonate. *Clin Orthop Relat Res.* 1993;288:214–218.
11. Kutlu A, Memik R, Mutlu M, Kutlu R, Arslan A. Congenital dislocation of the hip and it's relation to swaddling used in Turkey. *J Pediatr Orthop.* 1992;12:598–602.
12. Kwong KSC, Huang X, Cheng JCY, Evans JH. Acoustic transmission in normal human hips: structural testing of joint symmetry. *Med EngPhys.* 2003;25:811–816.
13. Kwong KSC, Huang X, Cheng JCY, Evans JH. New technique for early screening of developmental dysplasia of the hip: pilot study. *J Pediatr Orthop.* 2003;23:347–351.
14. MacEwen GD, Mason B. Evaluation and treatment of congenital dislocation of the hip in infants. *Orthop Clin North Am.* 1988;19:815–820.
15. MacKenzie IG, Wilson JG. Problems encountered in the early diagnosis and management of congenital dislocation of the hip. *J Bone Joint Surg Br.* 1981;63:38–42.
16. McCoy GF, McCrea JD, Beverland DE, Kernohan WG, Mollan RA. Vibration arthrography as a diagnostic aid in disease of the knee. A preliminary report. *J Bone Joint Surg Br.* 1987;69:288–293.
17. Mollan RA, Kernohan GW, Watters PH. Artefact encountered by the vibration detection system. *J Biomech.* 1983;16:193–199.
18. Mollan RA, McCullagh GC, Wilson RI. A critical appraisal of auscultation of human joints. *Clin Orthop Relat Res.* 1982;170:231–237.
19. Moore FH. Examining infants' hip - can it do harm? *J Bone Joint Surg Br.* 1989;71:4–5.
20. Ozdurak RH, Sezgin OC, Akin S, Korkusuz F. Vibration analysis of the human radius of elderly men. *Clin Orthop Relat Res.* 2006;443:94–100.
21. Schwend RM, Schoenecker P, Richards BS, Flynn JM, Vitale M. Screening the newborn for developmental dysplasia of the hip: now what do we do? *J Pediatr Orthop.* 2007;27:607–610.
22. Stone MH, Clarke NMP, Campbell MJ, et al. Comparison of audible sound transmission with ultrasound in screening for congenital dislocation of the hip. *Lancet.*1990;336:421–422.
23. Stone MH, Richardson JB, Bennet GC. Another clinical test for congenital dislocation of the hip. *Lancet.* 1987;25:954–955.
24. Uzel M, Ergun GU, Ekerbicer HC. The knowledge and attitudes of the primary care physicians on developmental dysplasia of the hip. *Saudi Med J.* 2007;28:1430–1434.
25. van der Perre G, Lowet G. In vivo assessment of bone mechanical properties by vibration and ultrasonic wave propagation analysis. *Bone.* 1996;18:29S–35S.
26. Wallace RG, Mollan RA, Kernohan WG. Preliminary report on a new technique to aid diagnosis of some disorders found in hands. *J Hand Surg Br.* 1985;10:269–272.
27. Woolacott NF, Puhan MA, Steurer J, Kleijnen J. Ultrasonography in screening for developmental dysplasia of the hip in newborns: systematic review. *BMJ.* 2005;330:1413.