Objective diagnosis of ADHD through movement analysis by using a smart chair with piezoelectric material

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Background: Attention-deficit/hyperactivity disorder (ADHD) is the most common neuropsychiatric disorder in schoolchildren. ADHD diagnoses are generally made based on criteria from the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition. The diagnosis is made clinically based on observation and information provided by parents and teachers, which is highly subjective and can lead to disparate results. Considering that hyperactivity is one of the main symptoms of ADHD, the inaccuracy of ADHD diagnosis based on subjective criteria necessitates the identification of a method to objectively diagnose ADHD.

Key Words
Attention-deficit/hyperactivity disorder;
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Methods: In this study, a medical chair containing a piezoelectric material was applied to objectively analyze movements of patients with ADHD, which were compared with those of patients without ADHD. This study enrolled 62 patients—31 patients with ADHD and 31 patients without ADHD. During the clinical evaluation, participants’ movements were recorded by the piezoelectric material for analysis. The variance, zero-crossing rate, and high energy rate of movements were subsequently analyzed.

Results: The results revealed that the variance, zero-crossing rate, and high energy rate were significantly higher in patients with ADHD than in those without ADHD. Classification performance was excellent in both groups, with the area under the curve as high as 98.00%.

Conclusion: Our findings suggest that the use of a smart chair equipped with piezoelectric material is an objective and potentially useful method for supporting the diagnosis of ADHD.

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1. Introduction

Attention-deficit/hyperactivity disorder (ADHD) is one of the most common childhood psychiatric disorders, affecting 3%–10% of children. ADHD diagnoses are generally based on criteria from the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-V). The diagnosis is made clinically on the basis of observation and information provided by parents and teachers, which is highly subjective and can lead to disparate results. The inaccuracy of ADHD diagnosis based on subjective criteria and the fact that hyperactivity is one of the main symptoms of this disorder necessitates the identification of a method to objectively diagnose ADHD. Several studies have attempted to record objective measures of movement in the study subjects, but these studies have numerous limitations. First, these studies employed actigraphy through the use of accelerometers and inertial measurement units worn by subjects, limiting the ecological validity of this method. Second, the infrared devices could only record parameters from some body parts. These studies have reported increased activity in patients with ADHD compared with controls.

First discovered by the Curie brothers in 1880, piezoelectricity is the change in the electric polarization of a material in response to applied mechanical stress or strain. Piezoelectric materials can be used in medical chairs in consulting rooms to precisely detect the movements of patients with ADHD without causing considerable obstruction to the patients. In this study, a piezoelectric material was inserted into a medical chair without affecting the chair’s outward appearance. This chair was then used to measure the movements of patients with ADHD for comparison with those of patients without ADHD (Fig. 1).

2. Patients and methods

2.1. Participants

The study cohort included 62 children (31 with and 31 without ADHD), all of whom were asked to sit on the smart chair and were examined by a pediatric neurologist or psychiatrist. All patients were unmedicated prior to the examination. To avoid bias in the comparison, all patients were asked to visit our department in the morning after breakfast. Children with a history of epilepsy, intellectual disability, drug abuse, head injury, or psychotic disorders were excluded from the ADHD group. ADHD was diagnosed according to the DSM-V criteria, and ADHD severity was evaluated using the Swanson, Nolan, and Pelham Questionnaire, Fourth Edition (SNAP-IV). The 26 items of the SNAP-IV questionnaire comprise 18 pertaining to ADHD symptoms (9 related to inattentiveness and 9 related to hyperactivity/impulsiveness) and 8 pertaining to oppositional defiant disorder symptoms as specified in the DSM-IV. The items are rated on a 4-point scale from 0 (not at all) to 3 (very much). ADHD is diagnosed based on the classification of patients’ symptoms into one of three subtypes: inattentive (ADHD-I; inattentive symptoms and few or no hyperactive symptoms), hyperactive/impulsive (ADHD-H);
hyperactive or impulsive symptoms and few or no inattentive symptoms), or combined (ADHD-C; both inattentive and hyperactive symptoms) ADHD. The patients without ADHD were diagnosed as having headache (11 patients), epilepsy (10 patients), dizziness (six patients), and tic disorders (four patients), which are common in pediatric neurology. Written informed consent was obtained from a family member or the legal guardian of each participant. This study was approved by the Institutional Review Board of Kaohsiung Medical University Hospital (KMUIRB-SV(I)-20190060).

2.2. Movement recording and analysis

This study used a smart chair connected to a recording device to measure the movements of participants (Fig. 1). The piezoelectric material was installed in the chair cushion. The piezoelectric material is a dielectric material that transforms mechanical stress into electrical charges. When mechanical stress is applied to the piezoelectric material, the piezoelectric material simultaneously generates an equal amount of charge on its surface. The positive and negative charges on the surface of the material gradually neutralize and the potential eventually decays to zero. The material must be repeatedly stretched and compressed for electricity to be continuously generated. A ceramic piezoelectric material was used in this study, with a piezoelectric voltage constant of approximately 300 pC/N. The signals were recorded at a sampling rate of 150 samples/s and at a voltage of ±7 mV. The digital signal was stored in the 12-bit resolution format. The recorder was powered by a battery and could record data continuously for more than 10 h. To ensure precise analysis for each patient, we excluded the signals generated when the patient initially sat down, stood up at the end of the examination, or moved while not being seated on the chair. The duration of recording was variable in each patient, lasting from 180 to 1536 s depending on their clinical situations. The mean durations of analyses in patients with and without ADHD were 624.71 ± 226.17 and 681.48 ± 313.42 s, respectively.

The recordings were performed during a routine visit. Generally, one physician, one nurse, one patient and the patient’s parents or legal guardian were in the consulting room during the recording process. The examination process was identical to a regular visit. The recording instrument was unobtrusive and nondescript, making it convenient and easy to use for both the physician and patient. However, an inherent problem with this system was ambient noise, which interfered with the signal during transmission, resulting in signal distortion. Such noise resulted in nonzero signals even when the chair was empty. Therefore, this study recorded only the signals generated due to participants’ movements and considered all other signals as noise. This was accomplished by using a Kalman filter to filter out noise and retain only the signals indicating actual movement. The system was also capable of detecting different movements. Fig. 2 presents the waveforms of sitting still, standing up, sitting down, swaying back and forth, and swiveling, demonstrating that the system could clearly represent the behavior of participants on the medical chair.

![Figure 2](image-url) Waveforms of different movements.

Patients with ADHD tend to fidget while sitting down, and this characteristic can be quantified through the variance (Var), zero-crossing rate (ZCR), and high energy rate (HER), which were used to analyze the signals in this study.

A greater variance indicated greater fidgeting by the patient and was defined as follows:

$$VAR = \frac{1}{N} \sum_{n=1}^{N} (x(n) - \bar{x})^2$$  \hspace{1cm} (1)

where $\bar{x}$ represents the mean of a given signal with $N$ samples and $x(n)$ is the $n$th sample.

ZCR referred to the proportion of signals that crossed zero within a period and was defined as follows:

$$ZCR = \frac{1}{2N} \sum_{n=1}^{N-1} |\text{sgn}[x(n)] - \text{sgn}[x(n-1)]|$$  \hspace{1cm} (2)

where $\text{sgn}[x(n)] = \begin{cases} 1, & x(n) \geq 0 \\ -1, & x(n) < 0 \end{cases}$

A higher ZCR indicated more frequent movement. The signal was also generated when the participant was sitting still.

A HER above a threshold of $Dv$ was used to identify when a participant made overly large movements. Herein, $Dv$ was set at a reasonable value of 0.05 mv to distinguish sitting still from other actions.

$$HER = \frac{1}{N} \sum_{n=1}^{N} \text{ture}[|x(n)| \geq D_v]$$  \hspace{1cm} (3)

where $\text{ture}[|x(n)| \geq D_v] = \begin{cases} 1, & |x(n)| \geq D_v \\ 0, & |x(n)| < D_v \end{cases}$.

The HER also indicated the cumulative time during which participants made overly large movements.
2.3. Feature discriminability analysis

To evaluate the discriminability of each feature combination between the ADHD and control groups, classification analyses based on six well-known classifiers, namely ada-Boost, decision tree, k-nearest neighbor (KNN), random forest, support vector machine (SVM), and extreme gradient boosting (XGBoost), were conducted. Seven feature combinations, namely Var, ZCR, HER, Var + ZCR, Var + HER, ZCR + HER, and Var + ZCR + HER (All), were considered, and each of the corresponding seven data sets were analyzed using the six mentioned classifiers. To obtain an unbiased comparison of classification results across different feature combinations with different classifiers, the well-known resampling strategy of 10-fold cross-validation with 10 repeats was applied. Moreover, classification performance was evaluated using four indices, namely sensitivity, specificity, accuracy, and area under the curve (AUC). Sensitivity was defined as the proportion of children with ADHD who were correctly classified as being in the ADHD group, whereas specificity was defined as the proportion of control participants who were correctly classified as controls. Accuracy was the percentage of ADHD or control class correctly predicted for all patients in both groups. The AUC was calculated as the entire two-dimensional area under the entire receiver operating curve (ROC) curve. The ROC curve was plotted with pairs of values of 1 – specificity and sensitivity corresponding to the classification results obtained using different threshold values of the considered feature. 1 – specificity and sensitivity were plotted on the x- and y-axes, respectively, and each ranged from 0 to 1. Higher sensitivity and lower 1-specificity indicated features with a higher specified threshold for distinguishing between the ADHD and control groups. The AUC provided an aggregate measure of the discriminability of a given feature across all possible thresholds. A higher AUC indicated that a feature could better differentiate between the ADHD and control groups.

2.4. Statistical analysis

All statistical analyses were conducted using SAS (v9.3; SAS Institute, Cary, NC, USA). Data are presented as means ± standard deviation. Measurements between patients with and without ADHD were conducted using the two-sample t test. Because three measures were obtained from the piezoelectric material, and to avoid multiple comparisons of inflation with type I errors, we applied a Bonferroni adjustment, and \( P < 0.05/3 = 0.0167 \) was considered statistically significant.

3. Results

In the present study, we enrolled 62 patients; 31 patients with ADHD and 31 age- and sex-matched control patients without ADHD (16 boys and 15 girls; 7 years 8 months ± 2 years 4 months in the ADHD group; 7 years 9 months ± 2 years 3 months in the non-ADHD group, \( P = 0.8808 \)). Overall, 13 boys had ADHD-C and three boys had ADHD-I; 10 girls had ADHD-C and five girls had ADHD-I. Of the ADHD subtypes, the most prevalent were ADHD-C and ADHD-H (78.0%–81.7%), followed by ADHD-I (18.3%–22.0%). In this study, 23 of 31 patients had ADHD-C; therefore, most of the recruited patients exhibited hyperactive symptoms. The SNAP scores obtained from parents and teachers were 38.09 ± 18.16 and 35.90 ± 11.88, respectively.

The Var, ZCR, and HER in patients with ADHD were significantly higher than those in patients without ADHD. The Var values in patients with and without ADHD were 1240.04 ± 323.71 and 62.42 ± 35.82 (\( P < 0.0001 \)), respectively; the ZCR values in patients with and without ADHD were 0.61 ± 0.17 and 0.09 ± 0.04 (\( P < 0.0001 \)), respectively; and the HER values in patients with and without ADHD were 0.32 ± 0.08 and 0.10 ± 0.03 (\( P < 0.0001 \)), respectively. We further divided the patients with ADHD into ADHD-I and ADHD-C groups (no patients with ADHD-H were included in this study) and compared their signal parameters. The Var values in patients with ADHD-I and ADHD-C were 1204.39 ± 694.80 and 1252.44 ± 363.13 (\( P = 0.9028 \)), respectively; the ZCR values in patients with ADHD-I and ADHD-C were 0.59 ± 0.33 and 0.62 ± 0.20 (\( P = 0.8789 \)), respectively; and the HER values in patients with ADHD-I and ADHD-C were 0.32 ± 0.18 and 0.32 ± 0.09 (\( P = 0.9921 \)), respectively. Fig. 3 provides an example of measurements from one patient with ADHD and one patient without ADHD; the patient without ADHD fidgeted significantly less than the patient with ADHD. In this study, the Var, ZCR, and HER were monitored in the consulting room. We also compared the four classification test performance indices, namely sensitivity, specificity, AUC, and accuracy, between six classifiers under each of the seven feature sets, as depicted in Fig. 4. The values of the performance indices were higher for feature sets containing Var than for the feature sets containing ZCR and HER. Among all combinations of feature set + classifier, Var and ZCR + XGBoost produced the highest sensitivity (93%), whereas All + KNN produced the highest specificity (94.50%), Var + SVM produced the highest AUC (98%), and All + KNN produced the highest accuracy (92.25%). Table 1 reveals the averaged ranking of each feature set corresponding to each classification performance index. Among all feature sets, Var + ZCR ranked first in terms of sensitivity and accuracy, and Var + HER ranked first in terms of specificity and AUC. Overall, the feature sets containing Var exhibited the best discriminability between the patients with and without ADHD.

4. Discussion

In this study, we found that the Var, ZCR, and HER were significantly higher in patients with ADHD than in patients without ADHD. Classification performance was excellent in both the groups, with an AUC as high as 98%. Thus, our proposed method constitutes a potentially useful and objective tool for supporting the diagnosis of ADHD.

The SNAP questionnaire was originally developed to serve as an objective tool for supporting the diagnosis of ADHD. The SNAP score has high validity and reliability, \( ^{16} - ^{18} \) one study reported poor interrater agreement between parents and teachers. \( ^{19} \) Additionally, parents’ ratings of inattention and hyperactivity/impulsivity were noted to be favorable.
predictors for research, but not for clinical diagnosis. Regarding teacher ratings, only hyperactivity/impulsivity scores were favorable predictors for both research and clinical diagnosis. The discrepancies between the SNAP scores obtained from the parents and from the teachers of patients with ADHD could lead to diagnostic uncertainty. We used a smart chair equipped with piezoelectric material to detect the activity of patients with and without ADHD and noted significantly higher Var, ZCR, and HER values in the patients with ADHD. The AUC for classifying patients with and without ADHD was as high as 98%. These results indicate that our method is an objective and convenient tool for supporting the diagnosis of ADHD.

The piezoelectric effect is a phenomenon wherein a material converts mechanical energy into electrical energy. Therefore, piezoelectric materials can be used to convert energy from the movement of a human body into electricity for powering wearable electronics. This category of sensing materials is of clinical interest because it can be used to diagnose and monitor respiratory disorders, damaged vocal cords, Parkinson’s disease, posture and movement, facial expressions, the degree of change in spinal

![Figure 3](image1.png) Measurements from patients with and without ADHD. The control patient fidgeted significantly less than the patient with ADHD. The relationship between the actual physical quantity $x$ (mv) and the digital value $n$ is: $x = 2.419 \times (n - 2045)$.

![Figure 4](image2.png) Comparison of classification test performance of sensitivity (a), specificity (b), AUC (c), and accuracy (d) between different classifiers among all feature sets.
breath basis. Piezoelectric materials can sense dynamic breathing of patients with sleep apnea on a breath-by-piezoelectric esophageal pressure catheter to monitor the many pathological gaits, including the parkinsonian gait. The flat-strike stance is one of the primary symptoms in between a heel-strike toe-off stance and a flat-strike stance. et al. used piezoelectric materials to analyze differences in pressure within a closed-loop environment, with high sensitivity and a wide measurement range. Chandel changes in pressure caused by changes in the movement of the patient.

This study has several limitations. First, although the Var, ZCR, and HER values were significantly higher in patients with ADHD than in patients without ADHD. The AUC for classifying patients with and without ADHD was as high as 98%. This suggests that the use of a smart chair equipped with a piezoelectric material is an objective and potentially useful method for supporting the diagnosis of ADHD, particularly in patients with ADHD-H and ADHD-C.

5. Conclusions

Most patients with ADHD have the ADHD-H or ADHD-C subtype. In the present study, the Var, ZCR, and HER values of movements were calculated using piezoelectric materials and were used as indicators for the objective evaluation of the movements in patients with and without ADHD. The Var, ZCR, and HER values were significantly higher in patients with ADHD than in patients without ADHD. The AUC for classifying patients with and without ADHD was as high as 98%. This suggests that the use of a smart chair equipped with a piezoelectric material is an objective and potentially useful method for supporting the diagnosis of ADHD, particularly in patients with ADHD-H and ADHD-C.

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Declaration of competing interest

The authors declare no actual or potential conflicts of interest.

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