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COŞKUN KAZMA

VECDİ EMRE LEVENT

MERVE ÇARDAK

NİZAMETTİN AYDIN

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Design and implementation of a low cost and portable tactile stimulator

Coşkun KAZMA[1,*], **Vecdi Emre LEVENT**[2], **Merve ÇARDAK**[3], **Nizamettin AYDIN**[1]

[1]Department of Computer Engineering, Faculty of Electrical and Electronics Engineering, Yıldız Technical University, İstanbul, Turkey

[2]Department of Computer Engineering, Faculty of Engineering, Fenerbahçe University, İstanbul, Turkey

[3]Department of Pediatric Psychiatry, Faculty of Medicine, Kocaeli University, Kocaeli, Turkey

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Abstract: When central nervous system has a problem, somatic area I and II respond to stimulation differently. Therefore, it is possible to identify some of the central nervous diseases when somatosensory on the fingertip is stimulated and responses are recorded and analyzed. We designed a system to stimulate the mechanoreceptors on fingertips. It is composed of a mechanical system for fingertip stimulation, an embedded controller, a control computer, and a software to control overall operation. During test, mechanoreceptors are stimulated according to the test protocols. Individuals' answers are recorded to be evaluated by the developed software. In this study, several design approaches for embedded controller were also examined and an FPGA based controller with the same functionality but higher performance was implemented. A test procedure was performed on 51 individuals at the department of pediatric psychiatry in a hospital, to investigate whether the sex has an effect on attention deficit and hyperactivity disorder.

Key words: Microcontroller, FPGA, tactile stimulator, neuroscience, ADHD

1. Introduction

The human body communicates with its environment through receptors surrounding its body. If the central nervous system encounters a problem, the somatic areas I and II respond to the receptors' pulses differently. When mechanoreceptors of fingertips are stimulated, the stimulation activity is transmitted to the somatosensory cortex.

There have been many studies concerning interaction between mechanoreceptors and somatic areas I and II. An excellent theoretical study on computational model based on previous physiological and psychophysical data for the human Pacinian (P) psychophysical channel can be found in [1]. It is reported that the model is able to predict the probability of detection in simple psychophysical tasks, psychometric functions and thresholds; simulates stimulating variable and fixed glabrous skin sites with different-sized contactors; and includes spatial variation of monkey P-fiber sensitivities. In [2], in order to compare the tactile threshold of children and young adults a test conducted to the two group of subjects with a tactile stimulator. The first subject group consist of 9 children aged between 9 and 11. The second subject group consist of 11 young adults aged from 21 to 27. According to the test result there is no significant result between children and young adult. This result therefore denies the loss of tactile sensitivity from childhood to early adulthood. In [3], while individuals' right-hand index finger volar surface was stimulated by mechanic vibration, their central nervous system (CNS) were displayed by functional magnetic resonance imaging (fMRI) and somatic area I (SI) reflected the changes in vibration amplitude applied to the finger during stimulation. Somatic area II (SII) did not respond to the

*Correspondence: coskun.kazma@gmail.com

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stimulation. Another research reported in [4] showed interaction between mechanoreceptors and the CNS SI and SII. In this study, a pneumatic tactile stimulator was developed in order to study cortical networks underlying foot sole. During the stimulation of foot sole somatosensorial, individuals' CNSs were displayed with the MRI. According to the test results that conducted with 7 healthy young adults, SI and paracentral gyrus were revealed contralaterally and SII bilaterally. In another research referred in [5], a tactile stimulator was designed that was not affected by magnetic field. A button press test was conducted on individuals during fMRI monitoring by this device. According to the test results, SI, putamen, cerebellum and bilateral medial frontal gyrus were evoked. In [6], a tactile stimulator developed to be used with fMRI was reported. Researchers conducted tests on 12 healthy individuals. According to the test results, 12 healthy individuals showed visuo-tactile synchrony-related modulations in bilateral temporo-parietal cortex. In [7], a new device that contains piezoelectric actuator was described. In order to assess the applicability of the device for the analysis of vibrotactile stimulation in humans, three studies were conducted using this device and fMRI. Test was performed on 8 individuals' left-hand digit 2 (D2) and digit 5 (D5) fingers. According to the test results, significant clusters of activation were found in SI, SII, subcentral gyrus, the precentral gyrus, posterior insula, posterior parietal regions (area 5), and the posterior cingulate. Also, digit separation in SI was possible for all individuals. Second study was done on new 6 additional individuals. The first study's main contralateral activation patterns were copied and it was observed that the discrimination of the digits in SI was improved. In the third study, it was observed that activated area increased in SII, and decreased in SI when the stimulation frequency was increased from 30 Hz to 80 Hz. In order to differentiate representation of neural signals of active touch, self-touch, and passive touch, a test procedure was conducted [8]. In order to perform the test, a soft brush was used for stimulation of both glabrous (palm) and hairy (arm) skin. Participants stimulated their left palm and left arm with soft brush using their right hand. The test results revealed a large, significant, positive blood-oxygen-level-dependent (BOLD) signal when individuals touched to their left palm and less activity was found in SI for touching to the arm. Also, the active touch neural signal was significantly higher than the passive touch in Brodmann area of the SI. In order to map topography of somatosensory cortex, a tactile stimulation test procedure was conducted as reported in [9]. During the test procedure, increased blood-oxygen-level-dependent contrast-to-noise ratio at ultrahigh field (7 Tesla) was used in order to measure the topographic representation of the digits of individuals when tactile stimulation was applied to individuals' left hand D1 through D5 and vice versa. According to the test results, researchers achieved to orderly map of the digits on the posterior bank of the central sulcus. In another research, in order to describe the number and internal organization of cortical fields, a test was conducted as described in [10]. Eighteen individuals attended to the test and individuals' lips, face, hand, trunk were stimulated and individuals' somatosensory cortex that is in the sylvian fissure was mapped according to the stimulations. According to the research referred in [11], a test procedure was conducted on 8 individuals in order to investigate human somatosensory system especially SII. Individuals' right hand D2, D5 and hallux were electrically stimulated. During the stimulation individuals were monitored by fMRI and researchers investigated reflection of stimulation on SI and SII. In [12], flow and interaction between somatosensory and motor signals in the CNS is extensively reviewed. In [13], a new device called the tactile spinning wheel (TSW), which can be used with EEG, was presented. While TSW was stimulating the fingertips, EEG was monitoring the individual's CNS. The test results showed that the stimulation was activated in CNS. In this respect, it is possible to obtain information from CNS by stimulating mechanoreceptors.

There are several similar studies reported in the literature. In [14], a tactile stimulator system called Cortical Metrics (CM) was reported. The CM consists of two parts. The first part consists of the control board

and the second part contains the adjustable haptic stimulator nozzle. The CM receives test parameters from personal computer and applies to the individual. According to the test protocol, CM stimulates the mechanoreceptors and desktop software asks questions to the participants according to the test parameters. After that, participants answer these questions by clicking on left and/or right buttons of the mouse. In another research referred in [15], a tactile stimulator was designed and developed to become an alternative to electric stimulator. Electrical stimulation further creates artifacts and causes discomfort which is usually not well tolerated in the awake child. There is a needle and a hydraulic system is used to move the needle up and downward. During the stimulation individuals' electric responses of the peripheral nerve were measured with magnetoencephalography (MEG). According to the results the tactile stimulation showed a more spatial focus activation of the primary somatosensory cortex when compared against the electrical stimulation. Researchers developed another tactile stimulator for human tactile studies referred in [16]. The tactile stimulus consisted of three parts. They were control unit, air handling unit and stimulation unit. Control unit commanded the air handling unit. Then the air handling unit deliver the stimulation power to the stimulation unit. Electroencephalographic and event-related potential (ERP) studies were done with this device. Studies confirmed the presence of N100 and P300 waves at standard electrode position C3 in the somatosensory area of the brain. In another research, a tactile stimulator was developed as referred in [17]. This device can simultaneously stimulate the visual and auditory senses using E-Prime software, which is widely used in visual and auditory sensory studies. This device consists of a control unit, drive unit and vibrator. This tactile stimulator system was able to stimulate any part of the body including the fingertips. In other research referred in [18], researchers developed piezoelectric polymer film-based resonating actuator for tactile stimulation. The tactile stimulator was composed of 3×4 stimulating dot arrays. Stimulator has 257.0 ± 1.5 nm displacement, output pressure of 339.1 N/m2, and response time of 0.7 ms when an input voltage of 80 Vpk (52.5 kHz) was switched at 2 ms intervals (250 Hz). Also, this device was experimentally tested. In [19], it is argued that manual stimulation application is time consuming, requires great care and concentration on the part of the investigator, and leaves many stimulus parameters uncontrolled by researchers. Therefore, an automatized computer-controlled stimulator was developed. Researchers developed a new tactile stimulator in order to use with fMRI as reported in [20]. Because there is a magnetic area in the field and patients must remove all metal objects from them before monitored by fMRI, using a tactile stimulator with MRI is difficult. In this study a new pneumatically driven tactile stimulator was developed and a test procedure was conducted on six subjects. Test results proved that pneumatically driven tactile stimulator could be used with fMRI.

Some studies on autism [21], migraine aches [22], the effects of alcohol consumption [23], traumatic brain injury [24] and Parkinson disease effects [25] were reported in the literature. [22] reports a study performed on individuals with migraines and healthy control individuals. According to this study three different types of test procedures were applied to migraines and healthy individuals. Test procedures were amplitude discrimination, temporal order judgment, and duration. Researchers tested temporal discrimination of crossmodal and unimodal stimuli on 13 control individuals and 14 individuals who have writer's cramp as referred in [26]. Researchers asked to subjects to discriminate whether pairs of visual, tactile, or visuo-tactile stimuli were simultaneous or sequential and which stimulus preceded the other. [23] reports test procedures applied to college students aged between 18 and 26 years old in order to investigate impact of alcohol consumption on a variety of centrally mediated functions of the nervous system. There is a study done on children with autism spectrum disorder (ASD) [27]. It is known that children with ASD react abnormally to tactile stimuli with altered pain perception and lower motor skills than the healthy children. According to the result, children with ASD had increased pain sensitivity,

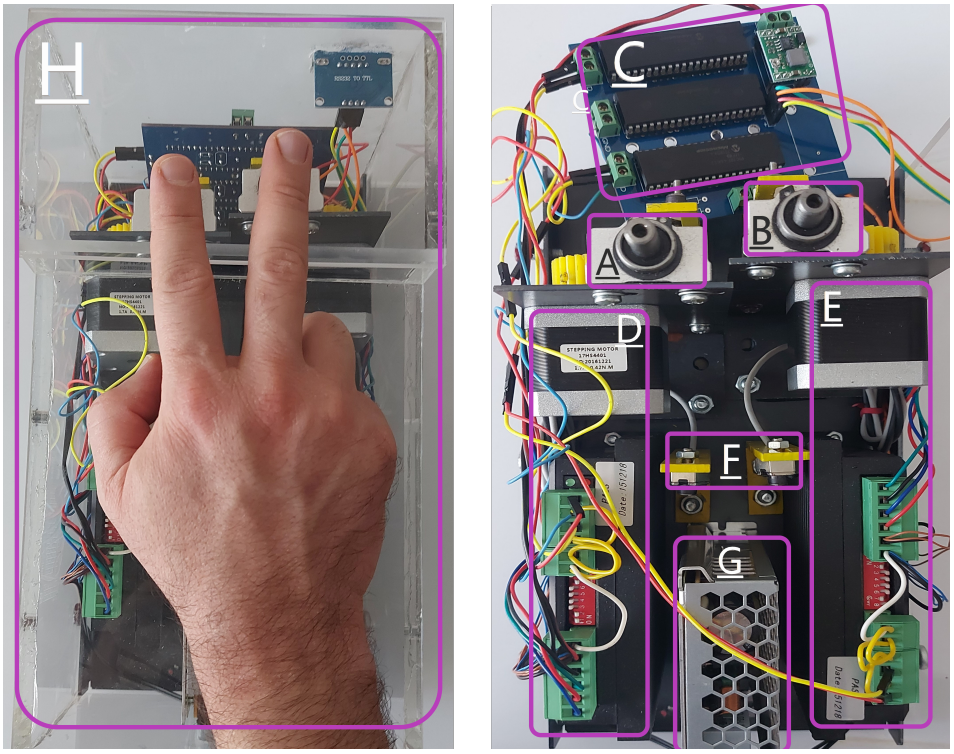
increased touch sensitivity in C-tactile afferents innervated areas and increased fine motor performance and proprioception when compared to healthy children. Abnormal somatosensory processing may contribute to motor impairments observed in Parkinson's disease (PD). It has been shown that dopaminergic medications alter somatosensory processing such that tactile perception is improved. In PD, it remains unclear whether the temporal sequencing of tactile stimuli is altered and if dopaminergic medications alter this perception. According to the research that was done in [25], tests were performed on 19 individuals. Nine (2 women) of them were in PD and 10 (5 women) of them were healthy aged between 47 and 73. It was reported that dopamine in PD reduces cortical-cortical connectivity within somatosensory cortex and this leads to changes in tactile sensitivity. Researchers tried to find how the brain activity and connectivity changed under tactile perception at early Parkinson state using fMRI as referred in [28]. A test procedure was conducted on 21 patients with PD and 22 controls. According to the results, bilateral sensorimotor cortex was hypoactive but the hyperactive regions were mainly in bilateral prefrontal cortex, bilateral cerebellum, and contralateral striatum in PD group during the stimulation. Also, researchers found that there was a significant decrease of total connectivity degree in ipsilateral SMA in PD, which was negatively correlated with the unified Parkinson's disease rating scale score. Therefore, this study illustrated that early PD was associated with not only altered brain activation but also changed functional connectivity in tactile perception. [29] reports a research done on 89 athletes, aged from 18 to 22 years old, in order to determine postconcussion return-to-play status. It was reported that CM4 system was able to provide a discrimination between concussed and nonconcussed individuals with 99 percent confidence that the two populations are statistically distinct. According to a study done on 80 healthy and 57 postconcussion individuals, a series of cortical metrics tests can detect traumatic brain injury with high sensitivity and selectivity without reliance on baseline testing [24].

2. Method

It is known that adaptation of somatosensory system on fingers after stimulation changes between 6.2 and 8.3 ms [30, 31]. Therefore, the developed tactile stimulator system stimulates the somatosensory system from 1 to 40 Hz, meaning that the maximum frequency of device is 40 Hz.

In this respect, we have designed a new system that impulses mechanoreceptors on the index fingertip and midfingertip. An earlier version of this system that includes a state-machine based preliminary FPGA design was reported in [32]. This earlier system was tested on 24 individuals, who were blue and white collar workers, in order to see if the system was able to identify fatigue status of the workers. The system was implemented as portable device by using inexpensive and easily obtainable components and can be reproduced quickly and easily. The test parameters such as frequency, amplitude and time discrimination can easily be defined, and are dynamically redefined according to the answers of the subjects during the test. There is no need for technical knowledge to use the system. Ability to use a mouse is sufficient for the subjects. A picture of the system and definitions of its components are shown in Figure 1. With the help of a desktop application, responses of the individuals are recorded on the SQL database in order to do statistical analysis. Tests are performed by stimulating the somatosensory that signals the "somatic sensory area 1" and "somatic sensory area 2" [33]. These tests are applied to the fingertips where the mechanoreceptors are located according to the test protocols in order to differentiate healthy individuals from nonhealthy individuals. The test procedure is illustrated in Figure 2.

The characteristics of the left and right stimulators must be identical giving the same response to the same inputs. Index finger and midfinger stimulator parts were tested at the low frequency and low amplitude.



A: index finger stimulator, B: midfinger stimulator, C: embedded board that receive stimulation parameters from computer software in order to drive stimulators, D: stepper and driver for index finger stimulator, E: stepper and driver for midfinger stimulator, F: infrared sensor that counts number of stimulations, G: system power supplier, H: test implementation.

Figure 1. System components and definition.

According to the test results, both stimulators have the same responses to the same inputs. For verification purposes, two infrared sensors were also used to measure frequencies and amplitudes.

The system was tested on 51 individuals, aged between 6 and 17, diagnosed as having attention deficit hyperactivity disorder in the Department of Pediatric Psychiatry, Faculty of Medicine, Kocaeli University. The number of male individuals were 32 and the number of female individuals were 19. The purpose of the test was to determine whether there was any statistical difference in the test group according to the age, sex and test type. Individuals were informed about duration of the test, how to start the test, how to answer the questions, and how to finalize the test. Additionally, they were asked to sign a consent form before starting the test procedure.

The test consists of frequency discrimination, amplitude discrimination, and time discrimination. Each test contains three different types of test parameters; frequency, amplitude, and starting time. Frequency test and its frequency parameter ranges between 1 and 40 Hz. Thus, index and midfingers can be stimulated between 1 and 40 times in a second. Let us assume that index finger is stimulated 1 time while midfinger is stimulated 40 times in a second. Because this test is most likely to be answered correctly by the most subjects, individual should get the lowest grade for these test parameters. In addition, 39 and 40 were hardest test parameters for individuals to distinguish and grade of that test parameters should be the highest (highest grade: 100 pts), if individual answers it correctly. In this respect, the following calculation for frequency test parameters is used.

$$A_f = 100/ABS(i_f - m_f) * [(if(i_f > m_f; i_f; m_f)/40 \quad (1)$$

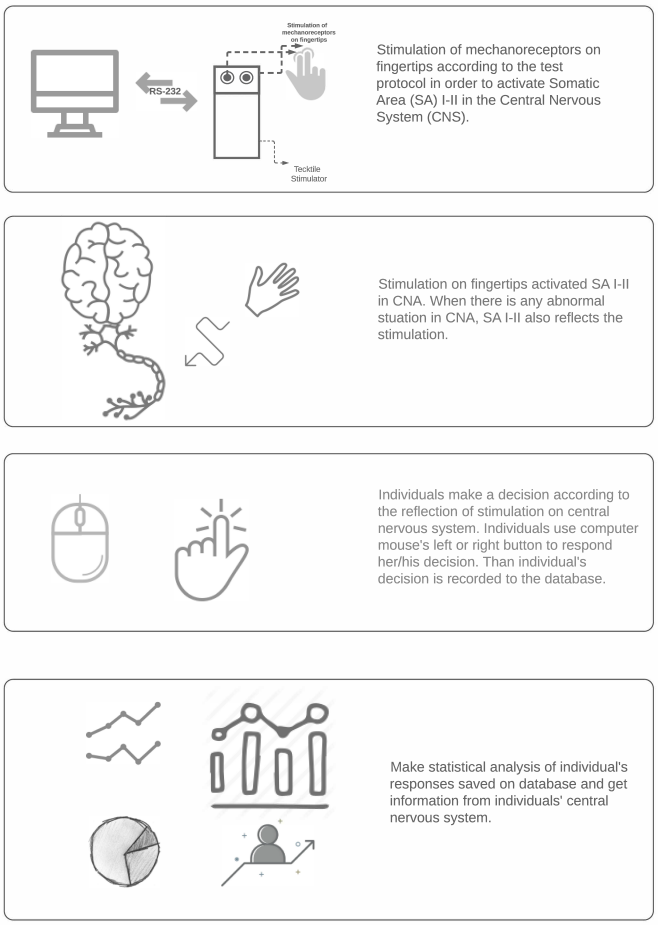


Figure 2. Test procedure.

In (1) where Af is the score for the frequency test, if is the frequency applied to index finger and mf is the frequency applied to midfinger.

The second test type is amplitude discrimination. Test parameters can be changed between 0.0471 mm and 3.768 mm. In addition, resolution of amplitude is 0.0471 mm. Let us assume that 0.0471 mm is assigned to index finger stimulator and 3.768 mm is assigned to midfinger stimulator. During the stimulation, index finger is pushed-up 0.0471 mm and midfinger is pushed-up 3.761 mm. The easiest to discriminate test parameters are 3.768 mm and 0.0471 mm and the hardest to discriminate test parameters are 3.7209 mm and 3.768 mm for amplitude. Therefore, highest grade should be 100 points for 3.7209 mm and 3.768 mm. Amplitude test parameters are calculated as follows:

$$A_a = 100/ABS(i_a - m_a) * 0,0471 \tag{2}$$

In (2) where A is the score for the amplitude test, ia is the amplitude applied to index finger and ma is the amplitude applied to midfinger.

The last test type is time discrimination. Test parameters can be changed between 1 ms and 1000 ms. Let us assume that 100 ms is assigned to index finger stimulator and 400 ms is assigned to midfinger stimulator. It means that when the system controller starts to apply test parameters, index finger stimulator waits 100 ms

and then stimulates the index finger. Also, midfinger stimulator waits 400 ms and then stimulates the midfinger. Thus, when the stimulation starts for index finger, midfinger is stimulated 300 ms later. There is 300 ms time difference between index finger stimulation and midfinger stimulation. The highest grade is 100 points when parameters are 999 ms and 1000 ms and lowest grade is assigned for the parameters 1 ms and 1000 ms. Time discrimination test parameters are calculated as follows:

$$A_t = 100/ABS(i_t - m_t) \tag{3}$$

In (3) where At is the score for the time discrimination test, it is the start-time applied to index finger and mt is the start-time applied to midfinger.

2.1. Machine specification

The designed tactile stimulator is composed of some electronic and mechanical components. The mechanical components are two rods that move vertically (±Y direction). During the test process, rods touches the index and middle fingertips to stimulate mechanoreceptors according to the test protocol by the help of a desktop software. Frequency of the vertical movement for each rod can independently be programmed between 1 and 40 Hertz, with 1 Hz resolution. In the current design, rods can move upward 3.768 mm maximum when the frequency of rod is 40 Hz. A 7.536 mm upward movement corresponds to 20 Hz rod frequency. The resolution of amplitude change is 0.0471 mm. In other words, rods can stimulate the finger tips by pushing fingers upward between 0.0471 mm and 3.768 mm at 40 Hz.

Test parameters are sent from desktop software to embedded board by using RS-232 protocol. Embedded board reads data and controls the stepper motors. All system components are explained in Figure 1.

2.2. Desktop control software

In order to measure functionality of central nervous system, three different types of tests using a desktop software developed in .Net C Sharp were prepared. First one is frequency test and its question is “which one touched more”, second test type is amplitude test and its question is “which one pushed upward”, and the last test type is time discrimination test and its question is “which one started first”. Test parameters should be defined and saved to the desktop software’s SQL database.

Desktop software sends parameters to embedded board and asks those three questions by starting the test process to the individuals. Subjects answer the questions through left or right mouse buttons and the answers are saved to the SQL database to be analyzed later.

3. System controller

We aimed to apply three different type of test procedures to the individuals in order to identify whether there is any abnormality in the central nervous system or not by stimulating index and midfinger. First one is frequency test as mentioned before. According to the test protocol, system stimulates the mechanoreceptors of index and midfingertips. System should start and finalize stimulation of each fingers simultaneously. In addition, number of stimulations to each finger might be different. For instance, system might stimulate index finger 5 times in a second and stimulate midfinger 7 times in a second. That means that the frequency for index finger is 5 Hz and the frequency for middle finger is 7 Hz.

In order to implement all these operations, an embedded board that includes 3 microcontrollers was designed. The system block diagram is shown in Figure 3. The main microcontroller controls other two

microcontrollers (left and right) that are dedicated to generate signals used to drive stepper motor that stimulate index and midfingertips. The process flows as follows: First, desktop software sends data to embedded board via RS-232. Format of the data is shown in Figure 4. Data includes test parameters for index and middle fingers. Main microcontroller takes command from the desktop and analyzes it. Then it separates the commands for left and right microcontrollers and sends to them. Left and right microcontrollers receive commands and do required calculations. When left and right microcontrollers are ready to operate the command, microcontrollers send "ready" command to the main microcontroller. Then main microcontroller responds by sending "operate" signal to the left and right microcontrollers at the same time. Thus, microcontrollers can start and stop simultaneously. Left and right microcontrollers have the same C code that is written in MicroC.

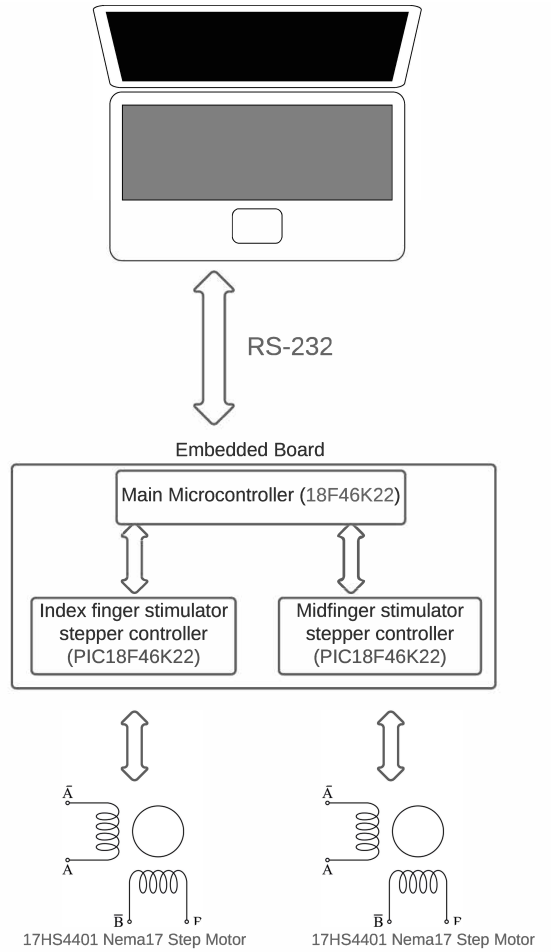


Figure 3. Overall system diagram.

Using three microcontrollers may seem as a waste of resources. However, there are two bottlenecks in using one microcontroller; limited memory and data transfer rate. In order to drive steppers, a square wave should be applied to stepper driver. When pulse goes from high to low, stepper rotates for one-step. It is well known that a basic microcontroller executes only one instruction at a time. Figure 5 shows square wave generator code for the stepper motor. Since we have two steppers that must operate simultaneously, there is no way that two codes can run simultaneously using one PIC microcontroller, which is a single core processor. Let us assume that the code in Figure 5 is for the left stepper. The code for the right stepper will have different

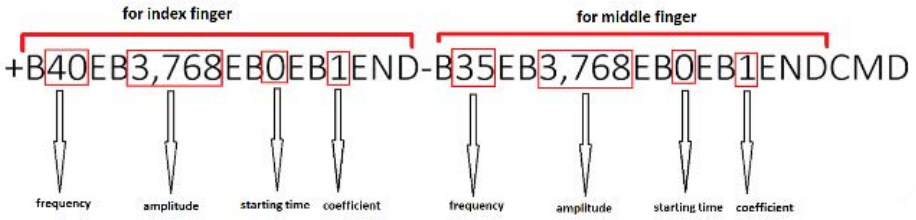


Figure 4. Data format.

parameter values and follow the code for the left stepper. Microcontroller will drive the left stepper first and then drive the right stepper. In fact, left and right stepper motors must begin and end simultaneously. Therefore, two microcontrollers generating square waves in one for-loop for two stepper motors and a main microcontroller to control them were employed.

In only one microcontroller implementation, in order to get left and right stepper motors run simultaneously, square waves for left and right stepper motors must be overlapped. Let us assume that we need to stimulate index finger 2 times and middle finger 3 times in a second. There should be 4 logic bits and 6 logic bits for left and right steppers, respectively, in order to create square waves. In order to get 2 Hz and 3 Hz square waves overlapped, we have to find the least common multiple, which is 12 for 4 and 6. Then we have to create 2 binary arrays representing square waves for left and right steppers. Thus, 111000111000 and 110011001100 represent 2 Hz and 3 Hz square waves, respectively, as shown in Figure 6. However, only a limited number of frequencies can be generated with this approach.

```
for (i=0;i<disp;i++)
{
        PORTD.F1 = 1;
        PORTD.F2 = 1;
        Delay_ms(100);
        PORTD.F1 = 0;
        PORTD.F2 = 1;
        Delay_ms(100);
}
```

Figure 5. Square wave generator.

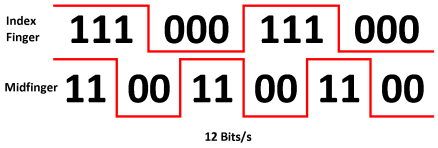


Figure 6. Overlap square wave.

As a test protocol, we may stimulate index finger 40 times and midfinger 39 times in 1 s (frequency of index finger: 40 Hz, frequency of midfinger: 39 Hz). Thus, to create 40 Hz frequency we need to have 80-bit data and to create 39 Hz frequency we need to have 78-bit data. The smallest common multiple of 80 and 78 is 3120. Then we need 3120 bits binary array for each stepper. Unfortunately, there will be not enough memory space for those two arrays. Therefore, with one microcontroller, we cannot apply this type of test protocol. The same problem exists in the amplitude test and the time discrimination test, complicating the memory problem even further. Therefore, we need to use 3 microcontrollers for embedded board.

Another problem in single microcontroller design is the limited data transfer rate. A square wave is created by switching pin of any digital port of microcontroller from TRUE to FALSE or FALSE to TRUE in one for-loop, as illustrated in Figure 5. Pins 1 and 2 of PORTD are initially TRUE (PORTD.F1=1, PORTD.F2=1). 100 ms later (*Delay*_ms(100)) they become FALSE (PORTD.F1=0, PORTD.F2=0), and then 100 ms later (*Delay*_ms(100)) they become TRUE (PORTD.F1=1, PORTD.F2=1) again. Thus, 1 square wave can be

created when for-loop runs 1 time. Angular motion is converted to linear motion through creamer. In this respect, considering the pinion size in the current design, the creamier can move 0.0471 mm when stepper motor rotates for one-step. In other words, when for-loop runs just only one-time, creamier moves 0.0471 mm vertically. In addition, about 74 square waves are needed in order to move creamier about 3.5 mm. Thus, creamier moves vertically about 3.5 mm when 74 square waves are applied to the stepper motor driver. In addition, 74 square waves are needed to get back creamier to the initial position. Therefore, 148 square waves are needed for one stimulation of fingertip and this was for only 1 Hz stimulation. When amplitude is 3.5 mm, 5940 square waves are needed for 40 times stimulation of fingertip. We can use ($Delay_$ms(x) (x: integer value for delay time in millisecond) built in delay function in for-loop while switching pin of any digital port from 1 to 0 and 0 to 1 in order to create a square wave. Also, 6 ms delay is enough to stimulate fingertips for 3.5 mm amplitude at 40 Hz frequency. According to the smallest common multiple solution, we cannot reach to the speed that we need because of the data transfer rate limit. Therefore, the maximum stimulation frequency was just 13 Hz at 3.5 mm amplitude.

In Figure 7, the code to drive steppers simultaneously in one loop for single microcontroller solution is given. Pins 2 and 6 of PORTD are stored in order to determine direction of the stepper motors. Pins 1 and 3 are stored in order to generate square wave. Line 7 if(LEFT[f]==1) and line 11 if(LEFT[f]==2) statements are used to control the generation of one square wave. Also line 15 if(RIGHT[f]==1) and line 19 if(RIGHT[f]==2) statement are used to control generation of the other square wave. Line 6 for(f=0;f<SCF;f++) statement determines the square wave frequency and line 5 for(t=0;t<iter;t++) statement determines the number of iteration of the square wave. In single microcontroller design, first we need to find smallest common multiple for two square waves, and then we need to create two binary arrays in order to store overlapped square waves. Speed of fetching square wave data from memory is also not enough to reach 40 Hz frequency. Therefore, the smallest common multiple solution cannot meet our needs and we decided to use 3 microcontrollers for embedded board.

```
1   void FreqAp(int iter,int SCF, short LEFT[],
2   short RIGHT[ ])
3   {
4     int f, t;
5     for(t=0;t<iter;t++){
6      for(f=0;f< SCF;f++){
7        if(LEFT [f]==1) {
8          PORTD.F1 = 1;
9          PORTD.F2 = 0;
10       }
11       if(LEFT [f]==2) {
12         PORTD.F1 = 0;
13         PORTD.F2 = 0;
14       }
15       if(RIGHT [f]==1) {
16         PORTD.F3 = 1;
17         PORTD.F6 = 0;
18       }
19       if(RIGHT [f]==2) {
20         PORTD.F3 = 0;
21         PORTD.F6 = 0;
22       }
23     }
24   }
```

Figure 7. Frequency generation method for single microcontroller.

4. FPGA prototype design

Tactile stimulation devices can be implemented with many different calculation structures. The devices realized with different structures have various advantages and disadvantages compared to each other. In the literature, tactile stimulation devices are generally based on microcontroller and field programmable gate array (FPGA) [34–36]. Microcontroller based systems have some limitations. Since microcontrollers are not capable of parallel operation, they cannot control multiple input/output pins at the same time. It is therefore not possible to vibrate the motors connected to the tactile stimulator at the same time with a single microcontroller. Therefore, the cost increases, the portability of the system decreases and the power consumption increases due to the use of multiple microcontrollers. On the other hand, developing a system with FPGA is costly in terms of development time. Implementing the first prototype of the system on the microcontroller is important to reduce debugging time. This is because combining a complex structure like FPGA with the tactile stimulator devices such as vibration motors without the first tests means that multiple components have not been tested yet. This significantly increases the debugging time. Therefore, first of all, the system needs to be tested with microcontrollers, which is a simple calculation unit, and the debugging process regarding how to use the peripherals should be completed. After this stage, it is necessary to proceed with an FPGA-based system.

Developing a system on FPGA is more difficult than developing on microcontroller. The complexity of parallel execution increases development time. Although a change in the algorithm does not affect development time in the microcontroller-based system, it can lead to the redesign of the entire structure in an FPGA-based system. Many different types of tests can be performed on tactile stimulator devices. All tests that may be applied to patients may not be used at the same time. Keeping the entire design in an FPGA at the same time is costly both in terms of power consumption and area required. However, it may be necessary to modify the arithmetic calculations in some tests. Such changes affect the FPGA development time. Another problem is that if a large development card is used, the system's mobility will be reduced. In order to maintain the mobility of the system, the design must be able to fit into a smaller capacity FPGA.

All these parameters show that making a fixed design will give faster results in the first place. However, design changes and optimization needs arise, the design will not be reusable. Therefore, it will be necessary to redesign each new need. Development time will increase exponentially. In order to reduce the cost and power consumption of the FPGA to be selected, a structure that automatically optimizes the most appropriate architecture is needed.

Tactile stimulation device developed on FPGA consists of 3 main modules. These are "data grabber", "motor drive parameter calculator", and "move controller" modules. The main elements and connections of the system are given in Figure 8.

The system receives parameters from serial port or Ethernet interface according to test types. The relevant interface and required protocols must be resolved and the parameter transferred to other modules in raw form. Data grabber module performs this process. The raw data which is the output of the "data grabber" module is fed in the "motor drive parameter calculator" module. In this module, 4 different parameters are produced by performing various arithmetic operations. Floating point units are used for arithmetic operations. The pipeline method is used to optimize the arithmetic units. The generated parameters are fed to the move controller module. The move controller module controls the stepper motors connected to their pins according to the parameters it receives.

Deep pipeline structures were used in the design. With the pipelining technique, it is possible to both go up to high frequencies and reduce the delay. Especially in small FPGAs. It operates at low frequencies due to

its production technology. The design produced by this method makes it possible to attach the corresponding brake in small FPGAs. The calculations without data dependence were started in parallel calculations. Figure 9 shows the system level pipeline. Architecture without pipeline technique is given in Figure 10. The calculations are completed later than the pipeline technique. This delay can be reduced by analyzing the data dependency of the data acquisition and parameter calculation modules.

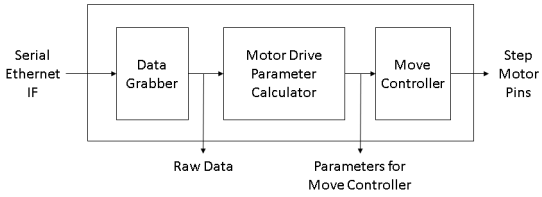


Figure 8. Tactile stimulator modules and connections.

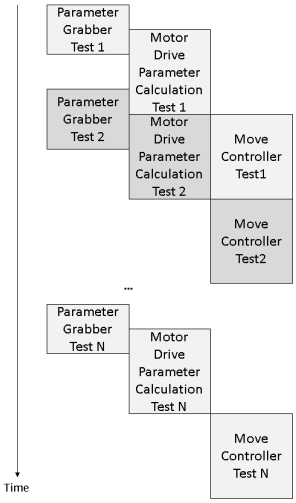


Figure 9. Tactile stimulator system level pipelining.

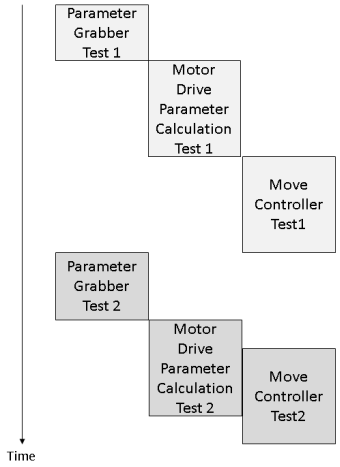


Figure 10. Tactile stimulator nonpipelined.

Optimizing the area and power consumption of the system to be implemented on the FPGA is very important. It may not be necessary to accommodate all the tests applicable to the patient within the system at the same time. A system with all tests can be discovered. However, in terms of area and power consumption a very bad situation will arise. Therefore, a hardware manufacturer framework has been developed according to the tests to be applied to the patient. The working mechanism of the relevant framework is given in Figure 11.

The parameters contained in the algorithm to be tested are fed to the estimator module. Estimator module determines design parameters for optimum area and power consumption point according to the model it contains. The design parameters found are fed to the code generator module to generate the input C code required by the high-level synthesis (HLS) module. The name of the HLS tool used is MAFURES (multiplexing aware function and register scheduler) [37]. MAFURES HLS takes the C code given to it and performs floating point unit (FPU) scheduling to extract the most suitable hardware. To do this, the CT (Cycle Time) parameter value is assigned to it. The tool produced is synthesized in the final stage with the Vivado synthesis tool from XILINX. The result is a highly optimized design. However, there may be better ones. Therefore, if we are not able to meet the targets, it is necessary to generate the code with the parameters close to the Perl Code Generator module and to produce hardware for HLS.

The estimator module is important for the tactile stimulator system to produce the most suitable equipment. Feeding a large number of designs to the HLS for space and power consumption increases synthesis times. In order to reduce the synthesis time, a tool that determines the parameters for which we will obtain optimum design has been developed. While this tool was initially developed, it was a bit costly in terms of time, making it more profitable than long-term use. First, the parameter generator module creates a large number of parameters to generate the model and generates the code. The HLS module converts these generated designs into register transfer level (RTL). The Vivado synthesis tool synthesizes the generated RTL codes, yielding area and power consumption results. All these results are transferred to a database. The relevant process is given in Figure 12.

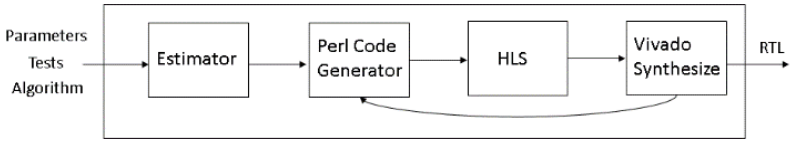


Figure 11. Framework RTL generation architecture.

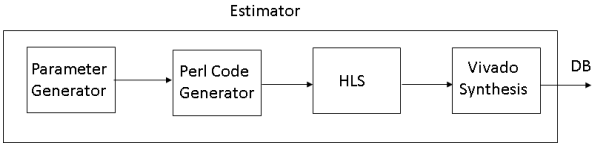


Figure 12. Estimator architecture.

Artificial intelligence algorithms were used to extract a model from the dataset. Since we have labeled data, classification algorithms have been tried. The algorithm that gives the highest performance was determined. Weka and MATLAB tools were used to determine the algorithm. A model is introduced by inserting the relevant algorithm into the estimator tool. After this stage, it can foresee the parameters for new future data.

5. Result

According to the test procedure for tactile stimulation, it was not possible to implement the system with one low-cost microcontroller because of processing requirement as it is mentioned before. Therefore, 3 same type low-cost microcontrollers were employed in the microcontroller-based stimulator. Memory requirements for the frequency test procedure of systems employing single and three microcontrollers are shown in Table 1.

Alternatively, for the FPGA-based solution, numerous synthesis processes have been performed with the developed framework. The synthesis process was carried out using Vivado from Xilinx. The target device was an Artix 7 series FPGA selected. A small selection of FPGAs was possible by eliminating the need for sheltering of all tests at the same time. This has led to a more optimized system in terms of space usage and power consumption. The FPGA resource utilization and available maximum operating frequencies before and after optimization are given in Table 2. The optimized design is synthesized as balanced and time optimized. The relevant results are shown in Table 3. The nonoptimized design is synthesized as balanced and time optimized. The relevant results are shown in Table 4.

As a result, it is seen that using FPGA is more advantageous when compared to microcontroller-based solutions. Moreover, more optimized results are obtained by using the mentioned methodologies instead of classical FPGA development methods.

Table 1. Memory requirement for the worst case scenario.

	With single microcontroller	With three microcontrollers
Frequency test	13 Hz @3,768 mm amplitude	40 Hz @3,768 mm amplitude
Required memory	5940 bits	No need

Table 2. Optimized vs. nonoptimized design synthesis.

	Slices	Slice flip flops	4 input LUTs	Frequency (MHz)
Optimized design	325	211	432	85.75
Nonoptimized design	813	744	1401	71.21

Table 3. Optimized design synthesis results.

	Slices	Slice flip flops	4 input LUTs	Frequency (MHz)
Balanced synthesis	325	211	432	85.75
Timing optimized synthesis	345	255	456	90.12

Table 4. Nonoptimized design synthesis results.

	Slices	Slice flip flops	4 input LUTs	Frequency (MHz)
Balanced synthesis	813	744	1401	72.31
Timing optimized synthesis	866	896	1543	78.35

The designed system was tested on 51 individuals (aged between 6 and 17 years) in the Department of Pediatric Psychiatry, Kocaeli University, Medicine Faculty to investigate whether the sex has an effect on attention deficit and/or hyperactivity disorder. The number of male individuals were 32 and the number of female individuals were 19. Before starting the test, individuals and their parents were informed about the test procedures and signed a consent form. Also, we obtained ethical approval from Yıldız Technical University Academic Ethics Committee (ethical approval number: 73613421-604.01-E.1804030304).

Initially, base test parameters shown in Table 5 were defined for three different test types. After applying first test parameters to the individual, next parameters are defined according to the individual's answer. The flow chart which is shown in Figure 13 illustrates how parameters are defined according to individual's answer and how the test procedure flows. In addition, for the frequency test, the amplitude parameter was defined as 3.0144 mm and the time parameter was defined as 0. For the frequency test, only the frequency parameter is changed according to the individual's answers. The amplitude and time parameters are constant as defined initially.

Table 5. First test parameters.

Test type	Question	Initial freq.	Initial ampl.	Initial time
Frequency	Which one touched more	35 Hz	3.0144 mm	0
Amplitude	Which one pushed upward	20 Hz	3.768 mm	0
Time discrimination	Which one started first	20 Hz	3.0144 mm	999

For the amplitude test, frequency and time parameters are constant and only amplitude parameter is changed according to the individual's answer. Also, for the time discrimination test, frequency and amplitude parameters are constant and only time parameter is changed according to the individual's answer. Amplitude test and time discrimination test were also performed according to the flow chart shown in Figure 13.

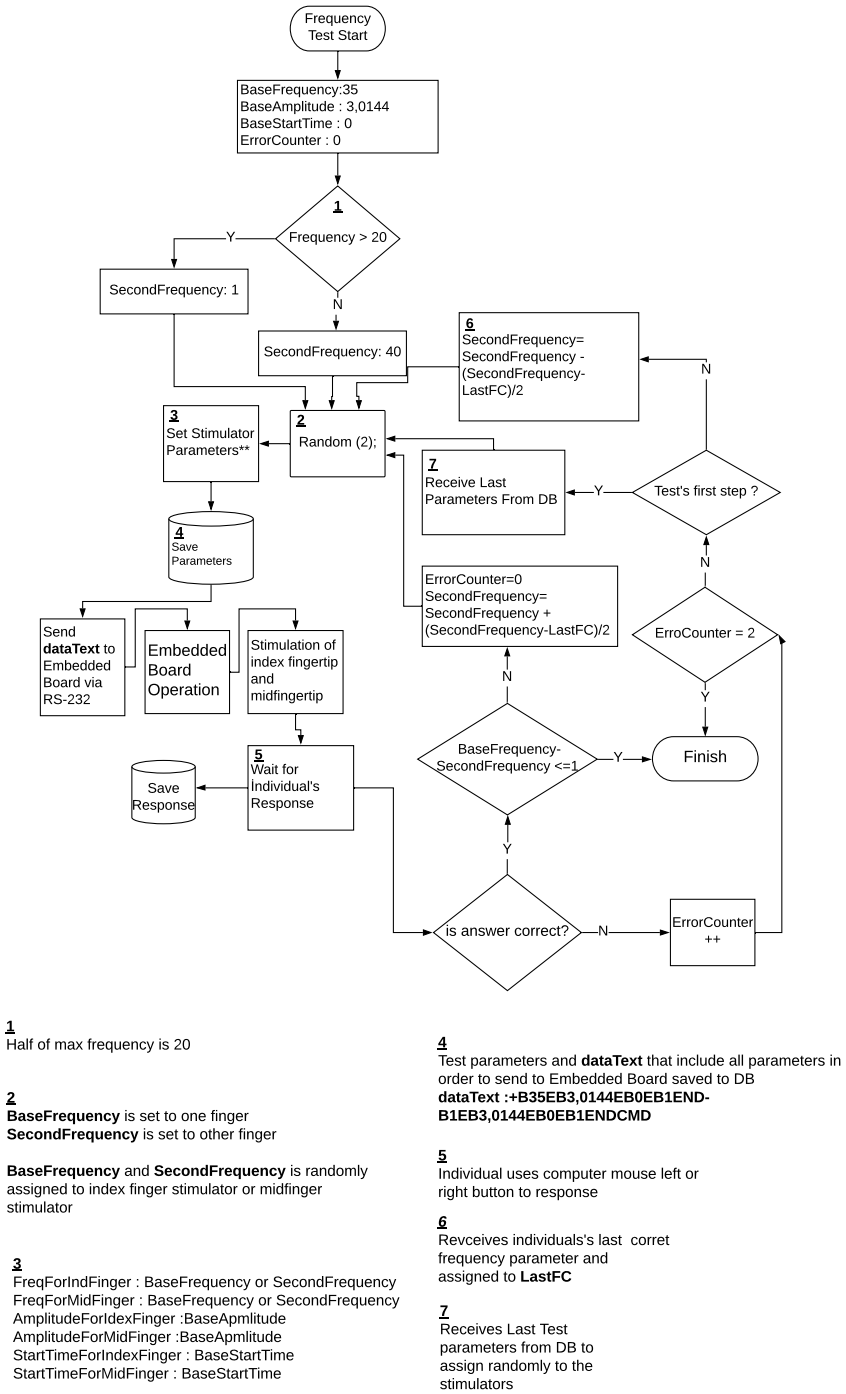


Figure 13. Flow chart of the test procedure.

5.1. Statistical analysis

The test results were analyzed using SPSS Statistics 25.0 software (IBM Corporation, NY, USA). Conformity of the data to normal distribution was assessed with the Kolmogorov–Smirnov test [38]. Variables with normal distribution were compared by independent samples t-test [39]. For the variables not fitting normal distribution,

the Mann–Whitney U test was used. Friedman (repeated measures ANOVA [40–42] on ranks) test was used for comparison of repeated measures. Pearson [43] or Spearman correlation analysis was used under normal distribution assumption for examination of correlation between variables [44]. Mean ± standard deviation (sd) and median (25th–75th percentiles) (q2(q1-q3)) was used as descriptive statistics. A value of $p < 0.05$ was accepted as statistically significant.

Table 6 shows comparison results of sex groups according to the age. The test results indicate that there is no statistically significant difference between male and female participants according to age ($p = 0.457$).

There is no statistically significant difference between male and female participants according to total number of "which one started earlier", "which one pushed up higher" and all questions ($p > 0.05$) whereas total number of the question "which finger was touched more" is found to be significantly larger in male participants than females ($p = 0.007$). This may be due to that female participants are more successful in realizing the touched finger than males (Table 7).

Total number of correct answers to the question "which finger was touched more" is found to be statistically significantly different between male and female participants. Male participants gave significantly more correct answers than females ($p = 0.009$). The number of correct answers to the questions "which one started earlier" and "which one pushed up higher" was not found to be statistically significant between sex groups ($p > 0.05$) (Table 8).

6. Discussion

In this study we designed and implemented a tactile stimulator in order to get information from CNS. Designed system can apply 3 different type tests. Each test parameters can be programmed by users and it is the strongest point of the system. Also, the system is mobile and it is easy to carry from one location to another.

In order to test usability of the system, we conducted a sex study. The test procedure was performed in the Department of Pediatric Psychiatry, Faculty of Medicine, Kocaeli University to investigate effect of sex on hyperactivity disorder. As it is known that attention deficit and hyperactivity disorder (ADHD) is a neuropsychiatric disorder characterized by problems with inattention, hyperactivity and impulsivity as mentioned in [45]. Nevertheless, according to some studies as mentioned in [46, 47], the ratio of male and female is 3 to 1. In our test group participant of the ratio is about 2 to 1 (number of male participants is 32 and number of female participants is 19).

Table 6. Comparison results of age between sex groups.

Variable	Male (n = 32)	Female (n = 19)	P
Age	9.88 ± 3.10	10.74 ± 3.78	0.457

As mentioned in [48], the ADHD is diagnosed and treated more often in males than in females. Background of the study is well-matched to our results. According to our result, male participant are more successful than the female participant, as male participants gave significantly more correct answers than females ($p = 0.009$) to the question of "which finger was touched more".

In the algorithm that shown in Figure 13, questions were asked according to the answers of the participants. That means that if participant gives correct answer to the related question, then parameters of the question getting closer to each other to become more difficult. Also, test procedure ended when participant

Table 7. Comparison results of total number of questions between sex groups (U: Mann–Whitney U test statistic, t: t test statistic, df: degrees of freedom).

Variable	Male (n = 32)	Female (n = 19)	U / t	df	p
Which finger was touched more (total number of questions) q2(q1-q3)	7 (5-8)	6 (3-7)	166.50	-	0.007
Which one started earlier (total number of questions) q2(q1-q3)	4 (2-9.75)	6 (2-9)	290.50	-	0.789
Which one pushed up higher (total number of questions) q2(q1-q3)	7 (5-9)	7 (5-9)	265.00	-	0.441
Total number of questions (mean ± sd)	20.66 ± 6.03	17.95 ± 5.74	1.599	39.479	0.118

Table 8. Comparison results of total number of correct answers between sex groups U: Mann–Whitney U test statistic, t: t test statistic, df: degrees of freedom).

Variable	Male (n = 32)	Female (n = 19)	U / t (df)	U	p
Which finger was touched more (total number of correct answers) (mean ± sd)	4.13 ± 2.04	2.58 ± 1.77	2.739 (49)	-	0.009
Which one started earlier (total number of correct answers) q2(q1-q3)	1 (0–6)	3 (0–5)	-	303	0.984
Which one pushed up higher (total number of correct answers) q2(q1-q3)	4 (3–7)	4 (3–6)	-	265.5	0.446

gives wrong answer two times in a row. Thus, result of the frequency test shows that male participants are more successful than the female participants.

Another study mentioned in [49] was performed on adult ADHD patients. According to that study suicidal ideation was significantly higher in females with ADHD and the difference was not significant in males. Thus, this study also matched with our results.

7. Conclusion

Knowing that somatic area I and II respond to stimulation differently, in this paper the design and implementation of a portable inexpensive tactile stimulator system to stimulate the central nervous system by using a number of design approaches is described. The results showed that the FPGA based design has a number of advantages over the other designs. Compared to microcontroller-based solutions, the FPGA can easily be programmed to control and parallelize the processes in the nanosecond range. Therefore, in this work the FPGA is preferred for reducing cost and system complexity and improving control accuracy.

Although the system may be used in many applications as mentioned in the literature review, in order to prove that it functions as intended it was tested on 51 individuals (aged between 6 and 17 years) in the Department of Pediatric Psychiatry, Kocaeli University, Medicine Faculty to investigate whether the sex has an effect on attention deficit and/or hyperactivity disorder. Preliminary results of the tests suggest that the system can be useful for obtaining some significant information from the central nervous system. Thus, specifically it is possible to conclude that this device has potential to be used in clinical research to assess some neurological disorders. However, the design needs to be improved further before being employed in proper clinical use. In the future, this system will be used not in assessing some other related neurological disorders only, but also in many other applications.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Data access statement

The designed system was tested on 51 individuals (aged between 6 and 17 years) in the Department of Pediatric Psychiatry, Kocaeli University, Medicine Faculty to investigate whether the sex has an effect on attention deficit and/or hyperactivity disorder. The number of male individuals were 32 and the number of female individuals were 19. Before starting the test, individuals and their parents were informed about the test procedures and signed a consent form. Also, we obtained ethical approval from Yıldız Technical University Academic Ethics Committee (ethical approval number: 73613421-604.01-E.1804030304).

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