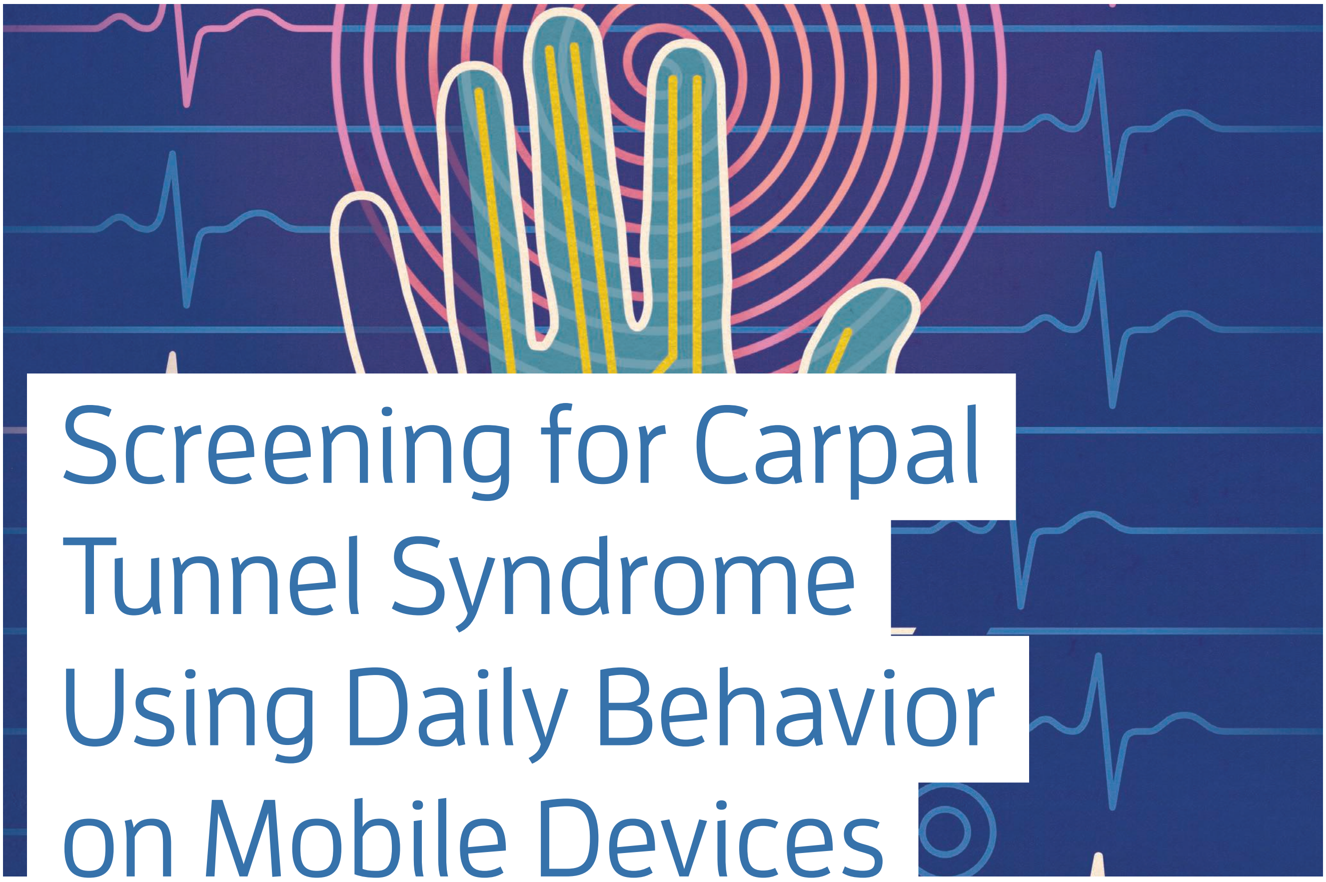

Screening for Carpal Tunnel Syndrome Using Daily Behavior on Mobile Devices

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Our vision is to detect hand disorders through daily behaviors so that people can unconsciously perform screening for the disorders without any additional actions being needed. To realize this vision, we employed mobile devices and focused on screening using two types of daily behaviors: writing and mobile game manipulations.

The hand is a motor organ with the most complex movements and delicate senses in the body. It not only performs daily activities such as eating, changing clothes, and dressing without interruption but also functions for work (writing, assembling machines, and operating computers) and artistic activities (playing musical instruments and drawing pictures). The hand is both an output interface for communicating one's feelings to others by shaking hands or using sign language and an input interface for reading information from braille. Therefore, the hand is

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probably the interface with the widest variety of inputs and outputs of any motor organ. In addition, the hand is closely related to the brain, and activities involving hand and finger movements (playing musical instruments and playing board games) act on the brain to reduce the risk of dementia.[1]

However, the degeneration of the nerves causes numbness, pain, sensory disturbance, and fine motor skills disorder (inability to perform fine hand movements) in the hands, making life difficult and possibly affecting brain function. Because the symptoms of the degeneration progress very slowly, they are difficult for patients themselves to notice, and by the time the patients become aware of the symptoms, the disease may have become severe and may require invasive treatment such as surgery. This not only places a burden on the patient but also consumes medical resources, such as doctors' operating time and increased medical costs. However, while specialized testing equipment is necessary for accurately diagnosing diseases, it is expensive and requires specialized technicians, so such equipment can be introduced in only a limited number of medical institutions.

It is known that neurological disorders that impair the hands, even in their early stages, exhibit characteristic physical movement patterns. Skilled physicians can identify these characteristics, but patients themselves or inexperienced physicians have difficulty doing so. Therefore, if we can screen for early symptoms of disorders by sensing physical movement patterns in everyday life outside of medical institutions, we could expect early detection, treatment, and prevention of severe disorders. Moreover, if hand disorders can be detected through daily behaviors, people will be able to unconsciously perform screening for disorders since no additional actions will be needed to detect the disorders (Figure 1). As a first step toward realizing this vision, we focus on screening using two types of daily behaviors: writing and mobile game manipulations. Writing is a regular behavior in our daily lives, such as writing memos, and mobile games are enjoyed by a wide range of people as mobile devices, such as smartphones and tablets, have become more widespread.

To detect these two types of behaviors, we utilized mobile devices. Mobile devices are used in a wide range of applications from personal to professional life and are essential in modern life. They are equipped with sensors (such as touch screens, RGB cameras, and microphones) that support user interaction, and we leveraged the sensors to detect the behaviors that can make it possible to evaluate hand disorders at remote locations other than medical institutions. In addition, it makes sense to leverage mobile devices for screening for hand disorders since mobile devices often require the use of hands and fingers to manipulate them, so people who suffer from hand disorders have difficulty manipulating mobile devices.

CARPAL TUNNEL SYNDROME

Carpal tunnel syndrome (CTS) is one of the most common peripheral neuropathies caused by compression of the median nerve in the carpal tunnel.[2] The prevalence of CTS ranges from 2.7% to 14.4% in southern Sweden with a population of 170,000 and is particularly prevalent in middle-aged and older women.[3] The prevalence appears to be similar in other countries. The initial symptoms of CTS are numbness and paresthesia in the area innervated by the median nerve, from the thumb to the ring finger. Since sensation in the hand and fingers is essential for manual dexterity, the loss of sensation makes it difficult to control hand movements such as pinching and affects manual dexterity such as button-clicking. As CTS progresses,

FIGURE 1. Our vision: a world where we can unconsciously screen for hand disorders during our daily behaviors. Users can detect the disorders just by playing a game on a smartphone or drawing a picture on a tablet by using a stylus. They do not need to take additional actions to detect the disorders.

the thenar muscle, located at the base of the thumb, atrophies. Atrophy of the thenar muscle limits the range of motion of the thumb and decreases grip and pinch strength, making it difficult to control force.

Physical examinations for CTS include the Tinel sign, in which the wrist is tapped with a finger to check for numbness and pain, and Phalen's test, pressing the backs of the hands together to see if the numbness and pain worsen. Although these tests are noninvasive and do not require any devices, they rely on the subjective assessment of the physician, which can lead to variations in sensitivity and specificity.[2] Nerve conduction studies (NCSs) observe the condition and compression of the median nerve by applying electrical stimulation through the skin.[4] NCSs can classify the severity of CTS, but the process is sometimes painful and requires specialized equipment. Ultrasound is a promising noninvasive alternative to NCSs, but its usefulness is still being validated.[5]

Studies have been conducted to quantitatively evaluate CTS at a lower cost than existing testing equipment. Noting that CTS impairs opposable thumb motion, some studies have measured the range of motion of the thumb by motion capture[6] or attaching a small gyroscopic sensor to the thumb.[7] The previous studies[6,7] confirmed that the CTS group had a more limited range of thumb motion than the non-CTS group, suggesting an application for screening for CTS. Although they used devices that are less expensive than existing testing devices, these devices are not widely available to the general public, making them difficult to use outside of medical institutions.

Conversely, studies have used mobile devices to quantitatively evaluate hand disorders, including CTS. Matsui et al.[8] developed a smartphone-based application that screens for cervical myelopathy (CM). CM is caused by spinal cord compression, which leads to numbness in the hands and impaired manual dexterity. Physicians often employ the grip and release (G&R) test, a gesture-based CM screening. The G&R test is simple because it evaluates the number of times a patient can G&R in 10 s (repeating the movements as fast as possible), but skilled physicians can also observe characteristic hand movements caused by CM. Matsui et al.[8] made it possible to quantitatively evaluate CM by video recording the G&R test. In addition, Matsui et al.[9] focused on the fact that CM's symptoms are similar to those of CTS; they applied the G&R test to CTS screening and developed a smartphone-based application that screens for CTS by video-recording the G&R test. Although Matsui et al.[8,9] evaluated hand disorders using mobile devices, they focused on the G&R test, which did not aim to integrate their screenings into our lives.

> **IF PEOPLE CAN BE SCREENED FOR CTS BY WRITING ALONE, THEY WILL NOT NEED TO TAKE ADDITIONAL ACTIONS TO DETECT CTS, AND EVERY TIME THEY WRITE, THEY WILL HAVE AN OPPORTUNITY FOR SCREENING, LEADING TO THE EARLY DETECTION OF CTS.**

SCREENING USING HAND DRAWING

Writing is a daily behavior and can be performed without any particular consciousness.[10] If people can be screened for CTS by writing alone, they will not need to take additional actions to detect CTS, and every time they write, they will have an opportunity for screening, leading to the early detection of CTS. Writing is also a behavior that requires manual dexterity, and CTS impairs fine motor skills, making it difficult for patients to write. A previous study[11] developed a special pen to measure the strokes and pressure of the pen and investigated the differences between CTS patients and healthy volunteers. However, this method is not easy to apply widely, because it uses a special pen, so the study did not lead to the development of a CTS screening system.

In recent years, high-performance pen tablets have emerged. While most conventional pen tablets are connected to a PC, Apple iPad Pro and Apple Pencil have the advantage of operating by themselves, enabling them to be used anywhere. Using these devices, we investigated the possibility of screening for CTS by simply drawing a spiral on the tablet screen[12] (Figure 2). A blue spiral is drawn on the screen of the tablet in advance, and users trace the blue spiral from the center. The blue spiral was set to a diameter of 4 cm to observe the users' fine motor skills. While the users traced the blue spiral, the tablet measured the stylus trajectory and pressure of the stylus tip over time.

Training data were generated from these time series data. First, the rate of change of motion was obtained by third-order differentiation and first-order differentiation of the time series data of the stylus trajectory and pressure of the stylus tip, respectively. The smaller the rate of change of motion, the smoother the motion.[13] Then, the frequency components were obtained by fast Fourier transform (FFT) of the differentiated time series data. A CTS inference model was constructed by training FFT time series data with a support vector machine (SVM), a type of machine learning.

We recruited 33 patients with CTS (seven males and 26 females, with a median age of 67 years and an interquartile range of 60–73 years) and 31 healthy volunteers (13 males and 18 females, with a median age of 64 years and an interquartile range of 55–72 years). Hand surgeons diagnosed the CTS group in the orthopedic outpatient clinic based on physical examinations and NCSs. The non-CTS group consisted of patients who had attended the orthopedic outpatient clinic or had been hospitalized for conditions other than CTS and had no hand complaints or abnormal findings on examination by the hand surgeons. All the participants manipulated the stylus with their right hand (the dominant hand) and drew three spirals, the last of which was analyzed.

Using leave-one-out cross-validation, the results of the experiment showed that the CTS inference model trained from the time series data of the pressure of the stylus tip had a sensitivity of 82% and specificity of 71%, while the CTS inference model trained from the time series data of the trajectory of the stylus tip had a sensitivity of 73% and specificity of 82%. These results indicated the possibility of screening for CTS by hand drawing.

We have confirmed that the trajectory of the stylus tip can be used to estimate CTS as well as the pressure of the stylus tip. Many inexpensive tablets on the market cannot measure the pressure but can measure the trajectory. Therefore, this screening for CTS could be implemented in inexpensive tablets.

We examined screening for CTS by drawing a spiral, but in the future, if we can screen using familiar everyday letters, such as Arabic numerals or one's name, we will be able to perform screening in contexts more consistent with everyday life, such as signing a credit card transaction.

SCREENING GAME USING THUMB MOVEMENTS

Tablet-based screening game

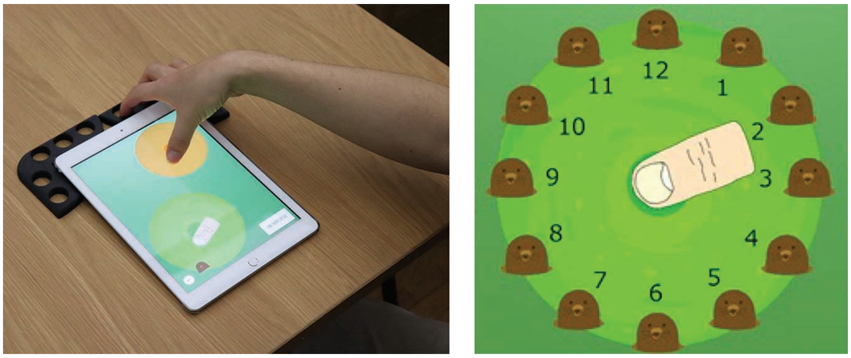
Mobile games have become popular and are enjoyed by a wide range of people as mobile devices have become more widespread. If mobile games can be integrated with technology to screen for CTS, users will be able to screen for

FIGURE 2. The tablet-based application using hand drawing for CTS screening. Participants drew a spiral of 4 cm in diameter using a stylus. The tablet measured the stylus trajectory and pressure of the stylus tip over time.

CTS subconsciously just by playing a game. As a first step toward integrating CTS screening into mobile games, we have developed a proprietary game application for CTS screening.[14] If our game application can demonstrate the potential of CTS screening, we will be able to embed the screening technology into commercially available mobile games in the future.

Our CTS screening game was developed for the Apple iPad. The users place their thumb on the orange circle on the screen, and an illustration of the thumb appears on the green circle (Figure 3). When the users slide their thumb, the illustration of the thumb moves in tandem with it, and the users manipulate the thumb illustration to touch animal characters that appear in 12 clock-like directions from the green center. The following three parameters were obtained from the thumb movements in each direction, so the number of dimensions of the parameters per subject was 36:

1. maximum velocity of thumb movement (cm/s) × 12 clock-like directions
2. average velocity of thumb movement (cm/s) × 12 clock-like directions
3. duration of thumb movement (s) × 12 clock-like directions.



(a) (b)

FIGURE 3. The tablet-based game application for CTS screening. (a) Participants used the application with their thumb. The index to small fingers were fixed to the holder. When the participant touched the orange circle with their thumb, the illustration of the thumb appeared and touched animal characters by controlling the illustration. (b) Animal characters appeared in 12 clock-like directions centered on the green circle.

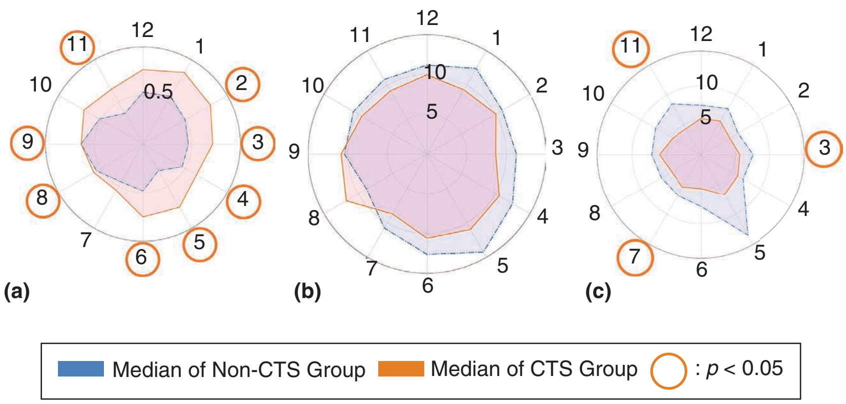


FIGURE 4. A representation of the median time to touch the animal characters. (a) The movement time (s), (b) the maximum velocity (cm/s), and (c) the average velocity (cm/s) to touch the animal characters in each direction. The orange circles indicate significant differences ($p < 0.05$) between non-CTS and CTS groups.

We recruited 22 patients with CTS (22 females for a total of 29 hands, a median age of 69 years, and an interquartile of range 59–80 years) and 11 healthy volunteers (11 females for a total of 11 hands, a median age of 67 years, and an interquartile range of 59–80 years) for the experiment. Hand surgeons diagnosed the CTS group in the orthopedic outpatient clinic based on physical examinations and NCSs. For the non-CTS group, volunteers were included if they had undergone a total hip arthroplasty at our hospital. Patients with a history of hand injury or surgery were excluded from the non-CTS group.

The results of the experiment showed that significant differences ($p < 0.05$) were identified in the directions circled in orange (Figure 4). Significant differences were clustered in the 2, 3, 4, 5, and 6 o'clock directions for the time of the thumb movement. When this game was played with the right hand, thumb opposition movements indicated clockwise from 12 to 6 o'clock, so the fact that significant differences were found in these directions suggested that the screening game successfully captured the characteristics of disturbance of thumb opposition movements caused by CTS.

Then, three parameters of the thumb movement were learned by the SVM. By leave-one-out cross-validation, the results showed that the screening game achieved 93% sensitivity and 82% specificity, suggesting its usefulness.

Smartphone-based screening game

Since smartphones are used more frequently than tablets,[15] a screening game for smartphones would help detect more potential patients. Therefore, the aforementioned screening game for tablets[14] was ported to smartphones[16] (Figure 5). To test the usefulness of the smartphone game, we recruited and tested participants, but since the number of participants visiting our medical institution was limited, it took time to build a training dataset for constructing a CTS inference model. Therefore, we constructed the CTS inference model by training only the thumb movements of healthy volunteers. This method was based on anomaly detection,[17] and we attempted to screen for CTS by detecting thumb movements that differed from those of healthy volunteers as abnormal.

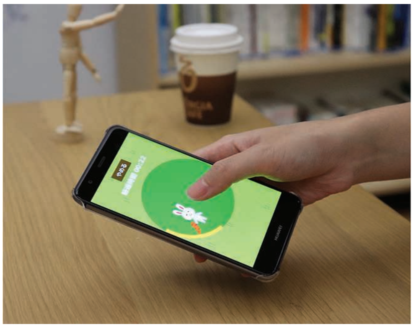


FIGURE 5. The smartphone-based game application for CTS screening. Participants touched and controlled a rabbit character with their thumb to touch vegetable characters appearing in one of 12 clock-like directions.

For anomaly detection, an autoencoder was used, which is a type of neural network consisting of three layers: an input layer, a hidden layer, and an output layer. The idea behind the autoencoder is that the hidden layer reduces the dimensionality of the data in the input layer, and the original dimensionality is regenerated from the hidden layer to the output layer. Small errors between the input and regenerated data are normal; anything else is abnormal.

We prepared the input images for the autoencoder by the following procedure. First, an image was generated with each direction as the height and time as the width, with the length of the width being 50 pixels, based on a 5 s × 10 Hz refresh rate of the smartphone screen (Figure 6). Next, the distance from the center of the circle to a vegetable character was defined as 1, and the distance between the center of the green circle and the thumb was assigned to each pixel. The farther the distance from the center of the green circle to the thumb, the larger the pixel value, and the whiter the color appears. The pixel value is set to 1 when the mother finger reaches the character, and the pixel value thereafter is set to 0. For the 600 pixels of the grayscale image, 600 dimensions were used as the input layer, and the hidden layer reduced the input to 10 dimensions.

For the experiment, 21 patients with CTS (five males and 16 females for a total of 36 hands, a mean age of 64.3 years, and a standard deviation of 12.2 years) diagnosed by hand surgeons based on physical findings and NCSs were recruited. A total of 15 healthy volunteers (three males and 12 females for a total of 27 hands, a mean age of 63.5 years, and a standard deviation of 17.6 years) were recruited from an osteopathic clinic. Participants with a history

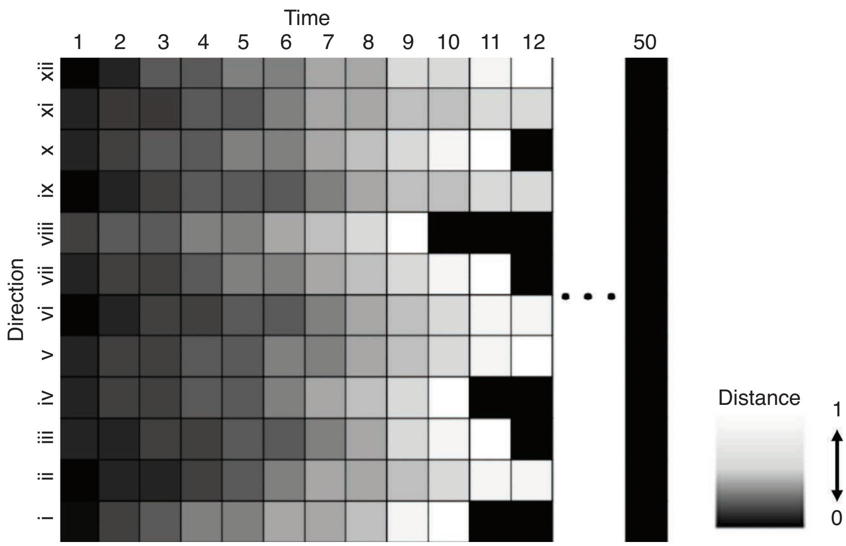


FIGURE 6. A grayscale image generated with each direction as the height and time as the width to train by a convolutional neural network. Defining the distance from the center of the green circle to the vegetable character in the application as 1, the distance between the center and the thumb was assigned to each pixel. The farther the distance from the center to the thumb, the larger the pixel value and the whiter the color appeared.

of hand injury or surgery were excluded from the non-CTS and CTS groups.

The anomaly detection was trained using 12 healthy hands, and 36 hands with CTS and 15 healthy hands were used as validation data. The mean-square error between the input and output layers was calculated as the reconstruction error for anomaly detection.

The results of the experiment showed a sensitivity of 94% and specificity of 67%, suggesting that the screening game may also be useful in screening for CTS. In addition, the CTS group took significantly longer mean times to touch vegetable characters at 6, 8, and 9 o'clock than the non-CTS group and were significantly slower in all directions in terms of the mean and maximum velocities of thumb movements. These results suggested that the screening game successfully captured the characteristics of disturbance of thumb opposition movements caused by CTS.

Our screening games showed potential for CTS screening. In the future, the screenings may be incorporated into existing mobile games manipulated using the thumb or even into software keyboard input operations on mobile devices.

TO REACH POTENTIAL PATIENTS

To reach more potential patients, people must be provided with the following options:

1. mobile devices to implement screening
2. hand motions required for screening
3. design of screening.

We described the development of a game-based CTS screening for tablets and smartphones. Since smartphones are more widely used than tablets, more potential patients can potentially be reached if a screening application is released for smartphones. However, smartphones also have their disadvantages. The recent increase in the size of smartphones has made it difficult to manipulate a screening application with one hand while grasping the smartphone with the thumb. Since the CTS screening application is targeted at older adults, who are more likely to be affected, older adults may not be able to successfully manipulate a smartphone with only one hand. On the other hand, the tablet-based screening application is used by placing it on a desk, so there is no such concern. Also, tablets have larger screens than smartphones, so users with presbyopia may be able to play the screening game more easily. Implementing the game on multiple types of mobile devices not only increases the possibility of reaching potential patients but also compensates for the shortcomings of each mobile device. Users can then choose the mobile device that best suits them.

IMPLEMENTING THE GAME ON MULTIPLE TYPES OF MOBILE DEVICES NOT ONLY INCREASES THE POSSIBILITY OF REACHING POTENTIAL PATIENTS BUT ALSO COMPENSATES FOR THE SHORTCOMINGS OF EACH MOBILE DEVICE.

Some patients with hand disorders may have numbness in the hands, while others may lack manual dexterity. To screen all of these patients, we need to screen for different types of hand motor requirements. For this reason, we proposed two types of screening: hand drawing and mobile game manipulations. Having screenings adapted to different symptoms could contribute to the detection of potential patients.

We have developed games to screen for CTS, as well as screening using hand drawing, one of our daily activities. Some users may like games, while others may not be good at games or may not understand the game system well. Those who like games can actively try the screening game, while others can try the screening with hand drawing. If a variety of screening content is prepared and catches people's attention, they will be more interested in trying the screening. In addition, the usability of screening applications is also important. Since the target users of our applications, older adults, tend to have low computer literacy, a user interface and user experience need to be designed that enable older adults to try screenings without hesitation. When we developed the applications, we increased the size of the fonts and software buttons used in the applications and reduced the number of software buttons to reduce the number of items that the user can select as much as possible.

LIMITATIONS

Our goal is to unconsciously screen for hand disorders during daily behavior, but there are several hurdles to overcome.

There are many hand disorders besides CTS (for example, the carpometacarpal joint of the thumb, trigger thumb, and de Quervain disease). Although the screening systems we have developed still have difficulty distinguishing among hand disorders, people with other hand impairments may test positive by using the screening application. If a positive result provides a reason to visit a medical institution, we can contribute to hand disorder detection. Ideally, it would be possible to distinguish among specific hand disorders, but it would be worthwhile just to infer that the patient has a hand disorder.

It is important to detect hand disorders in their early stages. To do this, we must recruit patients with early stage disorders and train machine learning with their data, which are currently limited. The reason for this is that these patients have few subjective symptoms, so they do not come to the hospital until the symptoms get worse. We tended to recruit those with moderate to severe symptoms in our hospital. As a first step, we developed screening systems to detect whether users have CTS.

Mobile devices are used in a variety of everyday situations. For example, when tired people use their smartphones, fatigue can affect data collection and result in false positives. We would like to collect data during low-fatigue periods. If we can detect when the user awakens based on smartphone usage and collect data when the user wakes up, we can reduce the impact of fatigue on data collection. In addition, if screening is performed at a fixed time each day, we can reduce the situational impacts of using smartphones for data collection.

From another perspective, every time you use your smartphone is a screening opportunity. Therefore, a majority can be taken from the number of positive and negative results in the daily screening counts, and the higher number can be used as the day's screening result.

User privacy could be violated if it becomes possible to screen for hand disorders by sensing daily behaviors, such as software keyboard input operations on mobile devices. Embedding a hand disorder inference model into mobile devices is a solution to this problem. The inference for hand disorders is performed within the mobile device, so user privacy is not violated.

We have achieved screening for CTS by sensing hand drawing and mobile game manipulations on a mobile device. In the future, we would like to integrate screening into the sequence of actions when using a mobile device, not just playing screening games, so that users can detect hand disorders unconsciously, such as software keyboard input operations and web browsing with the thumb. This will not force users to take additional actions for screening but could contribute to early detection of the hand disorder since every time they use their mobile devices, they will have an opportunity to perform screening.

Mark Weiser, a computer scientist, suggested that profound technologies blend into our daily living environment.[10] The screening technologies described in this article could be so integrated into our lives that they could watch over our health in the future. C

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