An Exergame System for Tenosynovitis Prevention by Softening Thumb Base

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Abstract—**With the increasing prevalence of tenosynovitis that can be caused by repetitive use of smartphones, effective rehabilitation methods have become crucial. To address this issue, we have proposed an exergame system for softening hand wrist while playing video games using hand gestures for wrist exercises. It is known that softening thumb base is often effective for preventing tenosynovitis in addition to hand wrist. In this paper, we present an exergame system for softening thumb base by extending our previous work. We have newly designed hand gestures with a rubber band that increases exercise loads to improve the effectiveness. The gestures are recognized by a Python program using MediaPipe library. In addition, to enhance accessibility and usability, we implement a web application for this system using Node.js. To evaluate the proposal, we asked 15 persons including one tenosynovitis patient, to play four video games installed in the system, and measured the maximum thumb movement angle of each person to investigate the finger flexibility. Besides, we evaluate their engagement levels through a questionnaire with the System Usability Score (SUS). The results observe the significant improvement in the thumb base flexibility and the positive feedback on user experiences.**

Keywords—**tenosynovitis, thumb base, rubber band, Python, MediaPipe, System Usability Score (SUS), web application, Node.js**

I. Introduction

Nowadays, for many people, smartphone use has become common in their daily lives around the world. Then, tenosynovitis [1, 2] has become prevalent in recent years because of its overuse. Tenosynovitis can be caused by prolonged use of the thumb or wrist while using a computer, smartphone, or other communication devices.

Physical exercises using hands and/or fingers can be beneficial for preventing and treating tenosynovitis. Hand exercises for stretching them or applying pressure to specific their areas can be effective in relieving symptoms. However, a lot of people, especially young people, may find that hand exercises may be too easy and boring. While many exercises must be integrated into daily life to achieve positive results, it can be very difficult to stick with them over the long term.

Playing video games while doing hand exercises can be an appealing way to make them more engaging and part of everyday routines. Generally, a gaming system designed for physical exercise is referred to as an exergame [3] system. In an exergame system for tenosynovitis prevention, multiple gestures are prepared to control specific key operations required to control a video game, and a user plays the game by appropriately selecting a gesture as a hand exercise.

Under this motivation, previously, we have studied and implemented an exergame system for preventing tenosynovitis running on a conventional PC [4, 5]. A user controls a video game offered in the system, using defined hand gestures that are recognized by a Python program using MediaPipe library [6] from captured images by a PC camera.

To prevent tenosynovitis, improving the flexibility of the wrist and thumb base of a hand is important. In the previous study, we designed hand gestures for softening the wrist and implemented the Python program to recognize them. For its evaluations, we asked students in Okayama University, Japan, to play the video games using the hand gestures. Before and after playing them, we measured the maximum angle for bending a hand to examine the wrist flexibility [7]. The results showed significant improvements of wrist flexibility by the proposed exergame system.

In this paper, we present an exergame system for softening the thumb base by extending our previous work. In this extension, we have newly designed hand gestures that will use a rubber band to increase loads of finger exercises. Again, they are recognized by the Python program with MediaPipe. While a user is playing a video game with various hand gestures, a rubber band is utilized to bind the fingers together and create the illusion of forces between them. A user must resist the forces by the band at changing the hand gesture with finger movements. In addition, to improve accessibility and usability for users, we also implement the web application for this exergame system using Node.js [8].

For evaluations of the proposal, we asked 13 younger people in Japan and China including one tenosynovitis

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patient and two older people in China, to play the installed four video games using the hand gestures one by one by following the given manual. After a user completed the games, we obtained their game scores and measured the maximum angle between the thumb and the forefinger of this user, to evaluate the thumb base flexibility. Besides, we evaluate the engagement level of a user through a questionnaire with the *S*ystem Usability Score (SUS) [9]. The result shows that thumb base flexibility is slightly increased in general by playing the exergame system.

The rest of this paper is organized as follows: Section II introduces the related work. Section III reviews the exergame system in our previous study. Section IV presents hand gestures for improving the thumb base flexibility in the exergame system. Section V presents the implementation of the web application system for the proposal. Section VI shows evaluations of the proposal. Section VII concludes this paper with future work.

II. Related Works

In this section, we explore related works to this paper, focusing on tenosynovitis, exergame, hand gesture recognitions with MediaPipe and finger flexibility.

A. Tenosynovitis

Muthu *et al.* [10] analyzed the etiology and complications of tenosynovitis of the hand.

They showed that excessive use of a smartphone led to repetitive thumb movements (>5,000 flexions and extensions per day), and there was a 32% prevalence of high-frequency hand work among programmers, musicians, and others. They also provided an anatomical basis for rubber band resistance training.

Ferrara *et al.* [11] comprehensively analyzed the conservative treatment of tenosynovitis in the wrist and hand, and illustrated that exercise therapy was most significant in improving their functions (41% reduction in DASH score) and preventing relapse (RR = 0.38).

Ahari *et al.* [12] showed that tendinitis triggered by use of a smartphone becomes an increasingly common health problem, especially for young and frequent mobile phone users. Their studies have shown that excessive typing is a significant trigger for tenosynovitis, and early identification and adjustment of usage habits is a key to preventing such problems. Tenosynovitis is risky to both elderly and young people with frequent use of mobile phones. Iwata *et al.* [13] introduced a typical case of tendonitis associated with smartphone use. They targeted a 22-year-old female who uses a mobile phone for an average of 8 hours daily and has a persistent pain in the radial tuberosity region of the right hand (VAS 7/10), aggravated by thumb movement. Finally, the subjects had complete pain relief, although they continued to perform preventive exercises (3 times per week). This paper confirms the causal relationship between smartphone use and tenosynovitis.

Rutkowski *et al.* [14] reviewed De Quervain's tenosynovitis in beauty practitioners. This study offers a traditional clinical approach, whereas our findings innovate home rehabilitation through gamification and contactless technology. Their studies emphasized the importance of short-term high-frequency training in the rehabilitation of tenosynovitis, which fits perfectly with the experimental design of our study of "1 minute per day × 5 days".

B. Exergame

Caserman *et al.* [15] focused on an immersive Virtual Reality (VR)-based whole-body motion recognition technique for the development of an exercise game (exergame), with a primary focus on aerobic training for obese adolescents. VR research provides feedback through virtual coaching, and this paper motivates users through game scores and angle measurements. We created an exergame system for tenosynovitis with rubber band resistance and gesture recognition, contributing to the technology of small joint rehabilitation. They also noted that Exergame, a virtual reality-based full-body exercise, significantly increased user exercise engagement, consistent with the high SUS score (80.5) results of our study, both validating the positive effect of gamification design on rehabilitation.

Husna *et al.* [16] focus on the design and evaluation of gesture control the program in motor games (exergames) for rehabilitation purposes. The real-time recognition accuracy reaches 89.2% based on the joint angle threshold method. This study provides a standardized framework for gesture design, while the present study expands the application of the technology in the field of tenosynovitis by means of an antilocking mechanism and a low-cost solution. The gestures in this study inspired us to design 6 gestures.

Vidyasagar *et al.* [17] proposed a framework for the design of a wearable device-based motor game (exergame), specifically for sensorimotor skills training. The "Adaptive Resistance Algorithm" was not implemented in our study, but it will be referred for dynamically adjusting rubber band resistance in future works.

The effectiveness of our rubber band-enhanced hand gesture is consistent with previous findings on resistance training for tendon rehabilitations. However, unlike existing video games focusing on wrist dexterity, the thumb-specific design in our study adds a new way to prevent tenosynovitis.

C. Hand Gesture Recognition

McIntosh *et al.* [18] proposed a gesture recognition system called EchoFlex based on Ultrasound Imaging (UI). EchoFlex's tendon motion capture validates the mechanics of rubber band training in this article.

Vidyasagar *et al.* [19] proposed a MediaPipe-based posture and gesture recognition system for gamified rehabilitation and physiotherapy and developed three training games for spinal correction, shoulder mobility restoration, and hand fine motor training. Their study included a module on fine motor training of the hand, which is directly relevant to the rehabilitation of thumb tenosynovitis.

Chandwani [20] developed a sign language recognition system based on MediaPipe. Adaptive thresholding strategy reduces misidentification in resistance training. In our paper, we reference the dynamic gesture library in their study.

Uboweja *et al.* [21] proposed an end-side real-time gesture recognition system. Users can record personalised gestures and fine-tune the model in 10 samples (>90% accuracy).

D. Finger Flexibility

Borghetti *et al.* [22] developed a sensor glove to accurately measure finger bending angles. With reference to its calibration method, they optimize the adaptation of MediaPipe to different hand shapes. The degree of the finger flexion was measured, which could be more effective in preventing tendinitis compared to previous studies. The method used in this study can optimize the accuracy of thumb angle measurements via MediaPipe in our study.

Kim *et al.* [23] have developed a finger rehabilitation robot designed to improve finger dexterity through mechanically assisted training. It adopts wire drive + exoskeleton hybrid structure, supports 5-finger independent motion control and adjusts flexion/extension degrees of freedom.

III. Review of Exergame System in Previous Study

In this section, we review the exergame system that is designed for wrist flexibility in our previous study [4, 5].

A. System Overview

Fig. 1 illustrates an overview of the system. A user controls a video game running on a web browser by using hand gestures. The gestures are recognized by our Python program that applies the MediaPipe library [12] to the images containing the user hand that are captured by a PC camera. MediaPipe can extract the coordinates of the 21 keypoints in one hand, as illustrated in Fig. 2 [24]. This Python program calculates the distances between the specific keypoints, and compares them with the given thresholds to recognize each hand gesture.

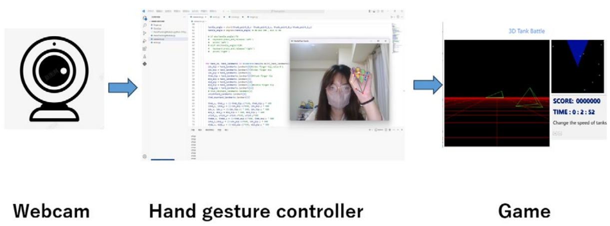

Fig. 1. Overview of exergame system with hand gestures.

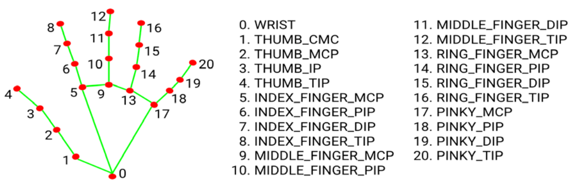

Fig. 2. 21 keypoints of one hand by MediaPipe.

We use Node.js and Express.js to build front-end and back-end of this interactive web application. Users can launch the gesture recognition program and select the game through the browser. The back-end handles the gesture recognition through the Python program. The front-end implements the user interface and the game control through JavaScript, which improves the accessibility and user experience of the system.

We combine a traditional hand rehabilitation training with a video game. The user is driven to complete specific gesture movements through game operations. This design improves the fun and the user participation of the rehabilitation training and can solve the problem of boring traditional exercise.

B. Hand Gestures for Wrist Flexibility

For this system, we defined the six hand gestures in Fig. 3 to control a game [25], intending to improve the wrist flexibility by randomly changing them. Four hand gestures were defined to represent pressing the left, right, up, and down keys in the keyboard. They change the direction of the wrist while all the fingers are closed together. For example, for the "up" key press, the player needs to make the hand palm be perpendicular to the horizontal plane and all the fingers upward. Two additional hand gestures were defined to represent releasing a key and pressing the space key.

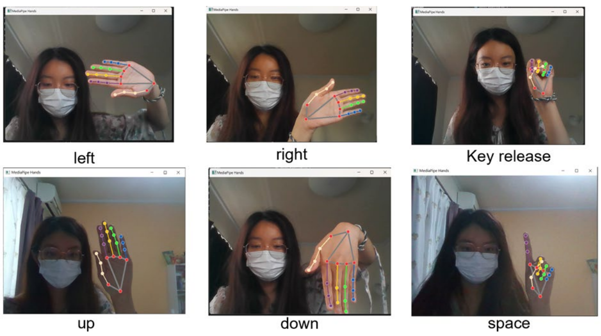

Fig. 3. Hand gestures for wrist flexibility.

C. Five Video Games

The programs of the following five video games were downloaded from the Internet and installed into the system. They are easy and simple to play with. They run on a web browser where they were implemented with HTML, CSS, and JavaScript.

1) Cave: In this game [26], a player needs to press the key properly to make the spaceship fly while avoiding collisions with walls through moving up and down. When the spaceship collides with a wall, the game is over. This game can be controlled by pressing only the space key. Fig. 4 shows the interface of this game.

2) Pick up fruits: In this game [27], fruits will continuously fall from the upper side at random locations of the game screen. A player needs to control the location of the basket to receive fruits at the bottom side of the screen by pressing the left or right key. This game can be controlled by pressing the two keys for left and right. Fig. 5 shows the interface of this game

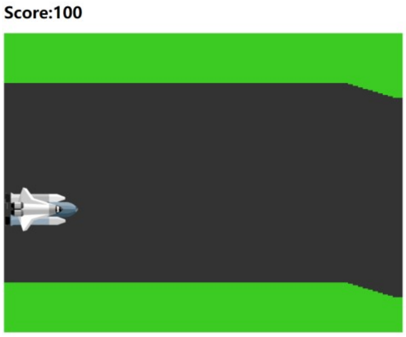

Fig. 4. Cave game.

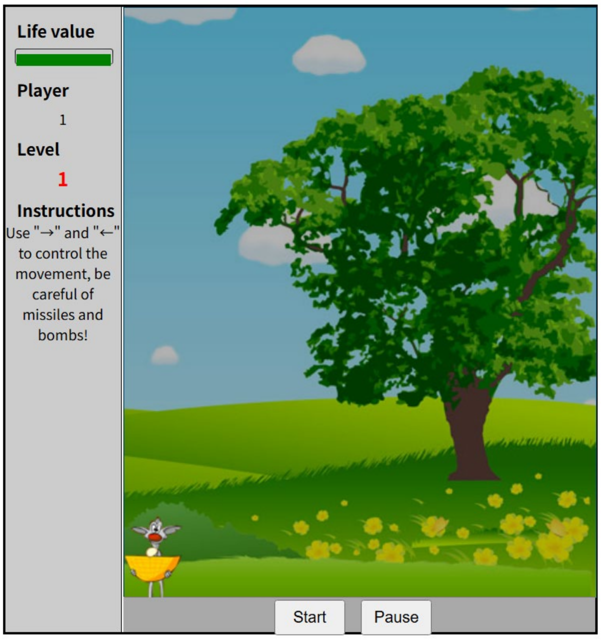

Fig. 5. "Pick up fruits" game.

3) Blocks game: Blocks Game: This game can be controlled by pressing the three keys for left, right, and space [26]. In this game, a number of different colored blocks appear at the top of the game screen [17]. The player can get a point by controlling the transmitter at the bottom properly and hitting the ball back so that it will collide with the block. When collided, the block will disappear and the point can be gained.

4) SnakeBite: This game can be controlled by pressing the four keys for left, right, up, down [26]. In this game, a player needs to control the moving direction of the snake to eat foods inside the game screen as many as possible [17]. Every time the snake bites a food, the player gets the point and the snake becomes longer. If the player can get the defined score within one minute, the game will be continued. Otherwise, the game is over.

5) 3DTank: This game can be controlled by pressing the five keys for left, right, up, down, and space [25]. The player maneuvers their tank forward, back ward, or rotates it while firing bullets to hit opponent tanks in this game, a 2D plane view that displays the player's tank and enemy tank positions in real time can be found on the upper right corner of the game screen.

IV. Hand Gestures for Thumb Base Flexibility

In this section, we present the hand gestures for improving the thumb base flexibility in the exergame system.

A. Hand Exercise with Rubber Band

To design proper hand gestures for improving the thumb base flexibility, we received an advice from a pain specialist regarding efficient hand exercises for this purpose. Then, he recommended the use of a rubber band that connect all the fingers together during hand exercises. This rubber band is placed around the fingertips as shown in Fig. 6 [27], and will cause a force for the fingers to be straight and close together [28]. This force can more efficiently soften the thumb base when a player tries to change the hand gesture to control a game.

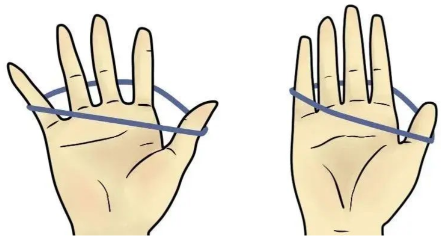

Fig. 6. Rubber band for hand.

B. Hand Gestures

For the thumb base flexibility, we defined the three hand gestures in Fig. 7 to control a video game. After several trials, we found that these gestures can be made by a player without difficulty while keeping the rubber band on the fingers. The thumb is either open (straight) or close (bended) among them. Thus, the thumb base can be trained by changing the hand gestures. One hand gesture will be used for either the right key or the space key depending on a video game, because either key is necessary in each adopted game in this paper.

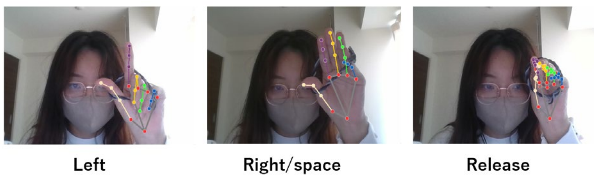

Fig. 7. Hand gestures for thumb base flexibility.

C. Hand Gesture Recognition Program

To recognize the hand gestures, we modified the Python program using the MediaPipe library. This program captures a hand image using a PC camera, extracts the hand landmarks of a hand called keypoints from the hand image, and identifies a hand gesture from the coordinate information of the keypoints.

The three hand gestures can be recognized by checking the states of the fingers, either open (straight) or close (bended). For the left hand gesture in Fig. 7, the thumb and index finger are open while the other fingers are close. For the right/space hand gesture, all the fingers are open. For the key release hand gesture, all the fingers are close. The state of the thumb can be hard to be detected correctly, because it is hidden by other fingers when they are closed. Thus, we do not check the state of the thumb in the hand gesture recognition.

Then, the distance between the keypoint for the finger tip and the keypoint for the hand bottom is calculated and compared with the given threshold, to examine the state. Actually, for the index finger, the distance between keypoints 0 and 8 is used. For the mid finger, the distance between keypoints 0 and 12 is used. For the ring finger, the distance between keypoints 0 and 16 is used. For the pinky, the distance between keypoints 0 and 20 is used. The distances are compared with the corresponding given thresholds.

When all of them are larger than the thresholds, the hand gesture is recognized as “space” or “right”. When the distance for the ring finger is larger than the threshold, the hand gesture is recognized as “left”. Otherwise, the hand gesture is recognized as “release”. Fig. 8 shows the Python code to detect “right/release”.

```
if results . multi_hand_landmarks :
    for hand_id , hand_landmarks in enumerate
    ( results . multi_hand_landmarks ) :
        thmb_tip = hand_landmarks . landmark [4]
        idx_tip = hand_landmarks . landmark [8]
        mid_tip = hand_landmarks . landmark [12]
        rng_tip = hand_landmarks . landmark [16]
        pnk_tip = hand_landmarks . landmark [20]
        # Changing coordinates to integers
        wrist_x , wrist_y = wrist . x * 640 , wrist . y * 480
        mid_x , mid_y = mid_tip . x * 640 , mid_tip . y * 480
        idx_x , idx_y = idx_tip . x * 640 , idx_tip . y * 480
        rng_x , rng_y = rng_tip . x * 640 , rng_tip . y * 480
        pnk_x , pnk_y = pnk_tip . x * 640 , pnk_tip . y * 480
        # Give threshold
        threshold_min = 0.12 * 640
        if ( thmb_idx_dist > threshold_min and
          thmb_mid_dist > threshold_min and
          thmb_rng_dist > threshold_min and
          thmb_pnk_dist > threshold_min ) :
          keyboard . press ( ’ space ’)
          keyboard . press ( ’ right ’)
          print ( " space / right " )
```

Fig. 8. Python code for right/space hand gesture.

V. Implementation of Web Application System

In this section, we present the implementation of the web application system for this proposal.

A. *Open Source Software*

We adopt two open source software in this web implementation.

1) Nodejs: Node.js provides the web application server environment on multiple PC platforms, including Windows, Linux, and macOS. It offers the interpreter and runtime environment for *JavaScript* codes on the server side. Thus, Node.js allows developers to use *JavaScript* on both front-end and back-end in web application systems.

2) Express.js: Express.js is a framework that provides a comprehensive array of features for developments of robust web applications. It is specifically designed for Node.js. It supports programs, compilers, code libraries, and APIs to provide benefits of customizations to expedite the development process.

B. *Lient-Side Implementation*

For the client-side of the web application system, the system start page and the game selection page are implemented using HTML, CSS, and JavaScript codes on a web browser. They interact with the server program through HTTP requests. Fig. 9 shows the client-side file directory structure.

```
/Interface
|— index.html        # Main webpage
|— css/              # Stylesheets
|   ├— styles.css
|— js/               # JavaScript files
|   ├— script.js
|— img/              # Image assets
```

Fig. 9. Client-side file directory structure.

1) System start page: Fig. 10 shows the web page to start running the hand gesture recognition program. On this page, a user can run the Python program including MediaPipe to recognize the hand gestures using a camera. When a user clicks the “Open Hand Gesture” button, it will send the request to the back-end, which will run the Python program.

Fig. 10. System start page.

2) Game selection page: Fig. 11 shows the web page to select a video game to play this time. On this page, a user can select one video game from the prepared ones. Currently, four games are prepared. When a user clicks one button, the front-end will send the request to the back-end, which will open a new tab and run the corresponding video game on this tab.

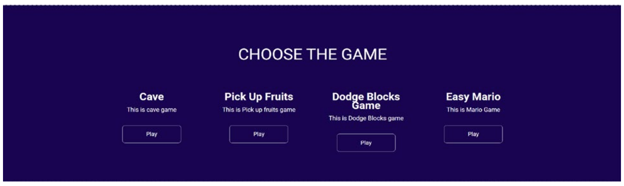

Fig. 11. Game selection page.

C. Server-Side Implementation

The Python program runs on the server when it receives the request from the system start page. Express.js is used to create the JavaScript interface program with the web pages. The following commands are included in the program:

1) Show system start page: **app.get('/', (req, res) => res.sendFile(path.join(dirname + 'interface/ index.html')))**

The index.html file is located inside the Interface directory. When a user visits http://localhost:3000/, this file is responded and appear in the browser.

2) Run python program: **app.get('/gesture, (req, res) => exec('"gesture.bat"', function(error,stout,stderr) res.send(stout)))**

Using exec() for Node.*js* child process, it runs the batch file gesture.bat and return the output to the client-side. This batch file contains the following commands:

echo off
start cmd.exe
start python gesture.py

D. System Usage Procedure

The following procedure explains the operation procedure of the exergame system.

Prepare and set up the necessary devices to start the system.

(1) Prepare and set up the necessary devices to start the system.
(2) Run Node.js and a web browser on a PC.
(3) Click the button "Open Hand Gesture" in the system start page to run the hand gesture recognition program.
(4) Choose one video game in the game selection page.
(5) Play the selected game using hand gestures.
(6) Keep the game score into a text file for analysis.

VI. Evaluation

In this section, we evaluate the proposed exergame system for thumb base flexibility through experiments. Two new video games called Dodge Blocks and EasyMario are used in our experiments, in addition to Cave and Pickup Fruits in the previous study, because they need two or three key inputs.

A. Two New Video Games

For the experiments, we introduce two new video games that were implemented using Python or JavaScript.

1) Dodge blocks: In this game [29], a player needs to control the moving direction of the blue block to dodge the rectangles by pressing the left key and the right key. The player can get a point when the block dodges a rectangle. Fig. 12 shows the interface of the game. In our experiments, we limited the playing time within 1 min.

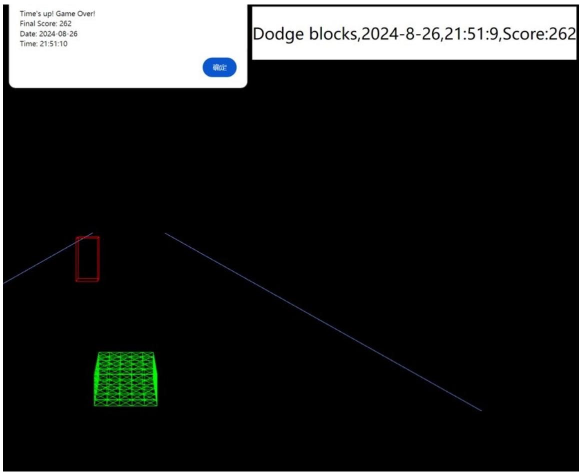

Fig. 12. Dodge blocks.

2) EasyMario: In this game, a player needs to jump the character Mario by pressing the release key to pick coins. The player can get a point when Mario picks a coin. Fig. 13 shows the interface of the game. In our experiments, we limited the playing time within 30 s.

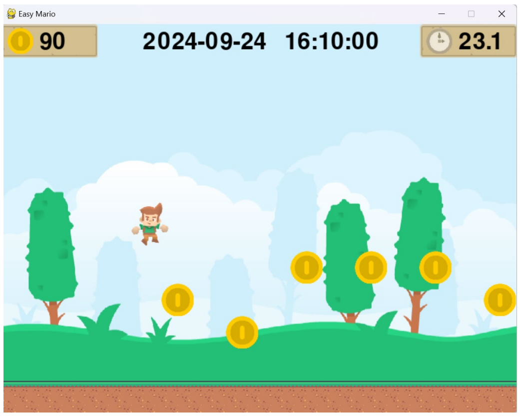

Fig. 13. Easy Mario.

B. Experimental Setup

For fair evaluations, we added the display of the game score and the playing time on the screen for any game. Then, we asked 13 younger people at 20–30 in Japan and China including one tenosynovitis patient, and two older people at 60–70 in China, to play the four video games using the hand gestures for thumb base flexibility. Each time a game play was over, the score was memorized so that the outcome of the game plays was recorded. Ethical approval was obtained from all the participants with the signed informed consent forms before the study.

When a person completed all of the four games, we measured the maximum opening angle between the thumb and the index finger of his/her hand, to investigate the change of the thumb base flexibility. Fig. 14 shows the hand gesture for this angle measurement. Besides, we also asked the student to answer to the questions on the system usability as a questionnaire.

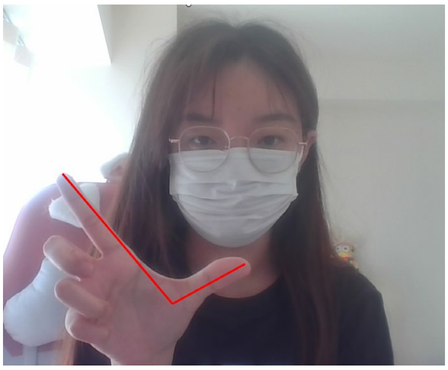

Fig. 14. Hand gesture for angle measurement.

C. Angle Measurement Results

The measurements of this maximum opening angle allow the assessment of the flexibility and functionality of the finger joint. The normal range of the angle is fundamental to maintaining the ability to perform a daily life and work [30]. If the range is below normal, it can indicate a limited joint function or an underlying problem.

Table I shows the angle measurement results of the 15 people including 13 young people and 2 older people in their 60 s (ID = 13, 14). We asked them to play the four video games using the hand gestures once a day during five consecutive days, and to measure the maximum thumb opening angle. We calculated the average of the angles for each time among the 15 people. Although the increase of this average angle is small, the thumb base flexibility was enhanced by playing the video games using the proposed hand gestures in the exergame system.

TABLE I. MEASUREMENT RESULTS OF MAXIMUM THUMB OPENING ANGLE

Times / Id	1	2	3	4	5
1	95	103	97	102	97
2	71	83	90	87	85
3	76	79	86	85	86
4	83	83	84	85	86
5	95	97	98	99	98
6	78	80	80	79	85
7	91	90	93	93	93
8	99	100	99	101	100
9	98	97	99	99	99
10	76	79	81	85	88
11	95	95	97	96	98
12	93	92	93	95	95
13	77	78	78	79	80
14	79	79	82	83	83
15	99	98	101	101	101
Average	87	88.9	90.1	91.4	91.7

Note: p = 0.00075(T-test)

From Table I, the average angle increased from 87.0°to 91.7° (+4.7°). In contrast, the angle of the tenosynovitis patients improved from 76° to 88° (+12°), which is much greater than the average. It suggests that the tendon stiffness of the tenosynovitis patients is significantly stimulated by the rubber band resistance training. Testers with ID = 13, 14 are seniors who had the smaller maximum bending angle than young people, but there was an increase in the maximum thumb opening angle. Active resistance training (rubber bands) verified to be effective in tendinitis prevention.

These results reveal the effectiveness of the Gamified Rehabilitation System (Exergame) combined with resistance training in preventing and improving tenosynovitis, particularly thumb base flexibility.

We performed the paired-samples t-test on participants' maximum thumb opening angles on the first (initial) and fifth (post-intervention) sessions to determine whether the gesture for softening thumb base significantly improves flexibility of thumb base. From Table I, $p = 0.00075 < 0.05$ is obtained, indicating that the difference between pre- and post-intervention is statistically significant and the proposed gestures for softening thumb base in the exergame system are valid.
Tenosynovitis Patient Results

Among 13 young people, the one at ID = 10 was a tenosynovitis patient. She was suffering from pains on the thumb base. Table I shows that the increase of her average angle was larger than the others. Actually, she felt that the pain of the thumb base was gradually reduced by repeating the game plays in the proposed system. However, she found that the one minute play of Dodge Blocks was too long and could cause fatigue in the hand for a tenosynovitis patient. For the other games, this student did not feel significant discomfort, where she thought that they could be used as a relief for tenosynovitis.

D. Questions for Questionnaire

After each student completed playing the four video games, we asked him/her to answer to the 10 questions made by ourselves on the system usability in Table II with five grades (1: strongly agree, 2: agree, 3: neutral, 4: disagree, 5: strongly disagree). The answer result for each question is converted to a 0–100 SUS score by being added together and multiplied with 2.5. A SUS score above 68 would be considered above the average and anything below 68 is below the average. The obtained average SUS score is 80.3, which indicates the A level or the top 10% of all the scores.

TABLE II. QUESTIONS ON SYSTEM USABILITY

ID	question
1	I think that patients with tenosynovitis can get benefit from hand exercises.
2	It is difficult to play the game with hand gestures.
3	The exercise game is enjoyable to play.
4	The system is not capable of accurately recognizing hand gestures.
5	I think the hand gesture is good for softening thumb base.
6	The gestures is difficult to remember.
7	I think the rubber band is useful for increasing loads of finger exercises.
8	I find the system has a lot of recognition delays.
9	I want to continue the exercise game using hand gestures.
10	I did not feel comfortable using the exercise game.

E. SUS Score Results

Table III shows the answer results to the questions from the students, and *SUS* raw and final scores. The average SUS final score among them is 80.5, where the lowest one is 62.5 and the highest one is 92.5. These scores suggest that the students positively evaluated the proposal for the thumb base flexibility. Thus, the effectiveness is confirmed.

TABLEIII. QUESTIONNAIRE RESULTS

User	answer to question										SUS raw score	SUS final score
	1	2	3	4	5	6	7	8	9	10		
1	5	4	5	1	4	1	5	1	5	1	36	90
2	5	2	5	1	5	1	4	1	3	2	35	87.5
3	4	2	5	2	5	1	4	2	3	2	32	80
4	4	2	3	5	4	2	3	2	5	1	27	67.5
5	4	2	5	3	4	1	5	2	4	2	32	80
6	1	1	1	2	4	2	4	2	5	3	25	62.5
7	4	2	4	3	5	2	4	2	4	2	30	75
8	4	3	5	4	5	1	4	1	5	1	33	82.5
9	5	2	5	2	5	1	5	1	5	2	37	92.5
10	5	1	5	1	4	1	5	2	5	4	35	87.5
11	5	1	4	2	5	1	5	1	5	3	33	82.5
12	5	1	4	2	4	2	5	2	5	2	32	80
13	5	3	5	2	3	2	5	2	5	4	30	75
14	4	4	4	1	4	2	4	2	4	3	28	70
15	5	1	5	1	4	1	4	4	4	3	34	85
Average											32.33	80.83

Our results demonstrate that the proposed exergame system significantly improved thumb base flexibility, with an average increase of 4.7° in the maximum thumb opening angle after five days of use. The System Usability Scale (SUS) score of 80.83 indicates strong user acceptance, particularly, enjoyment (Q3) and perceived benefits for tenosynovitis patients (Q1). Notably, the tenosynovitis patient (ID = 10) reported the reduced pain. The greater flexibility gain compared to healthy participants suggests the potential clinical use. Fig. 15 is a 100% stacked bars shows the distribution of SUS scores.

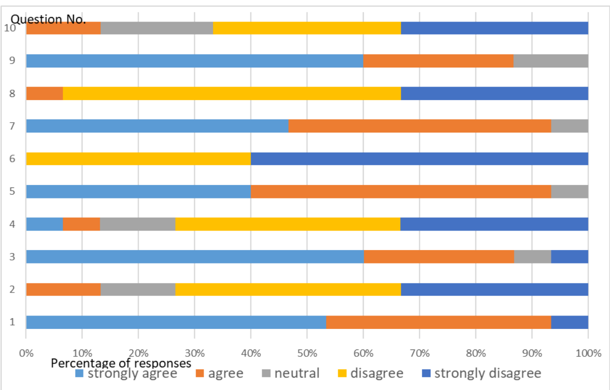

Fig. 15. Distribution of SUS scores (100% stacked bars).

Users with the higher SUS scores like ID = 9, score = 92.5 had significant improvements in their thumb angle, suggesting that system usability is directly related to rehabilitation outcomes. Fig. 15 visualizes the distribution of subjective ratings for each question. For example, in response to question 2, 13.3% (two people) found these gesture movements to be difficult. Comparison of the IDs revealed that the two people were seniors. More smooth movements may be needed. This is helpful for us to enhance afterwards.

The MediaPipe-based gesture recognition system by Python enables real-time, low-cost dynamic motion capture with a SUS score of 80.83, demonstrating excellent usability.

F. Discussions

1) Interpretation of results

The findings of this paper reveal the effectiveness of the Gamified Rehabilitation System (Exergame) combined with resistance training in preventing and improving tenosynovitis, particularly thumb base flexibility.

Short-term high-frequency training (doing the game once a day for 5 days) improved participants' maximum thumb opening angle by a mean of 4.7° to 5.6°, with patients with tenosynovitis (ID = 10) showing a more significant improvement (+12°). Active resistance training (rubber bands) verified to be effective in tendinitis prevention.

The MediaPipe-based gesture recognition system by Python enables real-time, low-cost dynamic motion capture with a SUS score of 80.5, demonstrating excellent usability.

2) Comparison with past research

In our previous study, we designed hand gestures for wrist exercises to improve the wrist flexibility. Then, we found that some tenosynovitis patients need finger exercises. Our literature survey found that most existing researches have focused on the gamification of the rehabilitation of a whole body or large joints, while there is a lack of quantifiable technical solution for precise resistance training of small joints of a hand. Our research has helped in the rehabilitation of small joints like fingers.

3) Implications

By introducing a rubber band for increasing the resistant force, this system increased the improvement in thumb flexibility by approximately 30%, validating the unique value of resistance training in tenosynovitis rehabilitation.

4) Limitations

Despite the positive results, the following areas for improvements may exist in this study: The sample size was small (*N* = 10) and contained only one confirmed patient. The ages of the subjects were 20–30, lacking data on the middle-aged and elderly population. No control group was set up, making it difficult to completely exclude a placebo effect. For technical aspects, the rubber band resistance is fixed, unable to adapt to different users' muscle strength levels. We do not have long-term follow-up data (>3 months).

In the future, we will identify and enroll at least 25 users. This game can be controlled by pressing the five keys for left, right, up, down, and space. Patients with tenosynovitis, develop adaptive resistance adjustment algorithms to dynamically adjust training intensity based on user performance.

VII. Conclusion

This paper presented the exergame system for enhancing the thumb base flexibility by extending the previous system to prevent tenosynovitis. Three hand gestures using a rubber band were defined, and two simple video games were newly introduced. For evaluations, 13 younger people in Japan and China including one tenosynovitis patient and two older people in China played the four games in the system for consecutive five days and the maximum thumb opening angles were measured to quantify the finger flexibility. The results show that thumb base flexibility was enhanced by the proposal. In future work, we will adopt different video games and hand gestures in the system for their variations. We will ask more persons at various ages, genders, and nationalities, including tenosynovitis patients and elderly to use this system, to collect evidence for the validity of the proposal.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Yanqi Xiao contributed to the conceptualization, software development, data collection, and original draft writing. Nobuo Funabiki supervised the project, provided methodological guidance, and reviewed and edited the manuscript. Irin Tri Anggraini participated in data analysis and provided research project design ideas. Haruya Fujiwara provided the design for the game. Jun-You Liu and Chih-Peng Fan responsible for providing methodological ideas and project guidance. All authors read and approved the final manuscript.

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