Essential Design Requirements for a Haptic-Assisted Hand Motor Training Systems in Stroke Rehabilitation: Insights from a Multidisciplinary Cohort

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Abstract. *Stroke survivors with disabilities must actively participate in targeted rehabilitation processes to recover their skills and prevent secondary impairments. Haptic technology offers the potential to restore motor functions by integrating visual perception and tactile sensation. However, designing a haptic-assisted hand motor training system for stroke patients poses significant challenges concerning how the program should be developed to achieve the most favorable rehabilitation outcomes. This research aimed to identify the essential design requirements tailored to the unique needs of stroke patients and their care providers, then develop a prototype hand motor training system. A diverse and inclusive cohort was selected for this study. The participants were provided with comprehensive details, ensuring a clear understanding of the objectives. In-depth interviews were conducted to gather valuable insights, which were then summarized and used as the foundation for developing the proposed rehabilitation system. The results highlighted integrating training games with a variety of difficulty levels, and hand-motor functions. The findings provide valuable guidance that could enhance the rehabilitation experience and improve patient outcomes. Moreover, the prototype system developed from these human needs could also be used for real-time measurement, thus facilitating the uncomplicated and rapid evaluation of post-training patients.*

Keywords:

stroke, rehabilitation, design requirement, motor training system, haptic

1. Introduction

Stroke, known as cerebrovascular disease (CVA), is a significant contributor to increasing mortality and disability rates. It occurs when blood flow in the brain is disrupted, either due to arterial blockage (Ischemic Stroke) or blood vessel rupture (Hemorrhagic Stroke). Symptoms include impaired balance, vision disturbances, and dizziness, which can lead to paralysis or even fatality [1]. Stroke is the second leading cause of death globally. Each year, 5.5 million people lose their lives to stroke, and 15 million new cases are diagnosed [2]. In Thailand, stroke affects an estimated 250,000 people, claiming 50,000 lives annually and ranking as the primary cause of disability and mortality [3]-[4].

Rehabilitation plays a vital role in enabling stroke patients to regain motor function and reduce disability, aiming to restore a normal or near-normal state. Traditional approaches, including motor- skill exercises, mobility training, and alternative medicine, often require significant assistance from caregivers [5]. To augment rehabilitation efforts, modern technologies such as haptic technology have emerged. Haptic technology facilitates tactile sensation, enabling the exchange of tactile information between users and virtual environments. Devices like 3D System's Phantom and Cyber Glove Systems provide haptic interfacing, enabling users to interact with virtual objects and offering an immersive experience through touch and sensory feedback [5]-[6]. These advancements hold great promise for stroke rehabilitation.

The objective of this research was to investigate the design requirements that lay the foundation for developing a haptic-aided rehabilitation system that not only achieves effective treatment outcomes but also improves the workflow of healthcare professionals. To accomplish this, surveys and small group discussions were conducted with medical specialists, engineers, stroke patients, and their families at a local hospital. These interactions proved invaluable in gathering insightful perspectives and identifying the desired functions of a rehabilitation system specifically tailored for stroke patients. Prototype software was then developed and presented to demonstrate how the specific requirements of related stakeholders were considered and integrated into the software design.

2. Related Works

Hospitals and rehabilitation centers serve as bustling hubs of interaction among patients and therapists. However, the visual aspects of these environments often lack excitement and engagement. Fortunately, haptic technology, such as robotic treatment and virtual reality, has emerged as a means of creating captivating sensory experiences [7]. In the context of this technology, haptic devices are physical tools that provide individuals with sensory or force feedback to individuals, allow them to make sense, and interact with simulated or virtual environments [5]. There has been a growing interest in the integration of haptic systems, which can be broadly categorized into hardware and software solutions.

Hardware-focused systems aim to devise mechanisms that incorporate force feedback into rehabilitation processes. These types of systems can be used to improve balance and reduce body sway in various postures and ground conditions, as reported in a previous research study where kinetic haptic inputs of young, healthy participants and stroke patients were analyzed [8]. In this study, a Phantom Omni® device was employed along with a waist-worn smartphone. An android app that operated in the background on the phone delivered mediolateral (ML and anteroposterior (AP) tilt angles to a PC that used Phantom Omni® for kinesthetic haptic input. Other benefits of hardware-type haptic systems are related to hand and finger training. A Haptic Indirect Feedback Hand Function Device (HIFHFD) and a training program were developed and utilized to evaluate the perceived benefits in chronic stroke survivors [9]. Participants with post-stroke durations ranging from 5 to 120 months were recruited for this study. Randomized variations in functional training features included force, range of motion, coordination, and dexterity, all aimed at improving hand function.

Another notable innovation involves the development and testing of a fingertip cutaneous haptic stimulation system for exoskeleton-assisted hand rehabilitation, leveraging 3D-printed pneumatic actuators [10]. This system aimed to improve stroke patients' training participation and motor function recovery by estimating contact forces on the fingertips during virtual interactions with objects, such as a glass of water. Recent advances in the hardware-based system have focused on downsizing and improving user-friendliness. A wearable haptic system utilizing asymmetric vibration was developed to offer improved guidance for patients or the elderly engaging in self-rehabilitation [11]. This led to enhanced motion learning accuracy, showcasing the technology's potential to guide patients through self-rehabilitation. Valverde-Arredondo and Carrasquilla-Batista [12] later discussed the design process for a haptic interface capable of evaluating hand strength, facilitating upper-limb rehabilitation exercises, and integrating Internet of Things (IoT) capabilities. A working prototype was created using 3D printing and an existing haptic controller, enabling the collection and transmission of rehabilitation activity data to an IoT platform.

In contrast to hardware-focused systems, software-driven approaches aim to develop haptic-assisted software that not only enhances usability and user experience but also motivates patients to consistently engage in their recovery activities consistently. Early research software-based systems have transformed rehabilitation activities into games. For example, the "Marble Maze" where a haptic device (Geomagic® Touch) and a Styrofoam board were combined to create games for wrist and hand rehabilitation [13]. In this game, players must guide the marbles to their destination within a specified time to prevent them from falling off the path. A survey questionnaire was used to evaluate the participants' satisfaction, assessing factors such as motivation to play games, enjoyment, interest, and overall satisfaction with the game. The next generation developed a Haptic Virtual Environment (HVE)system coupled with a Phantom Omni® to investigate whether cognitive fatigue influenced the coordination performance of wrist movements during rehabilitation [14]. With this tool, it was possible to analyze circular strokes performed by both patients and healthy individuals, ultimately comparing their wrist coordination, and noting the impact of increased fatigue on performance. In parallel, Yeh et al. [15] developed a touch VR system, known as a 3D game, which simulates touch pinching to aid in motor function recovery. This versatile VR system, compatible with various operating systems, incorporates hand-strengthening exercises, squeezing, and lifting tasks. Experiments demonstrated the system's effectiveness in stroke rehabilitation.

Newer generations of software-based systems, similar to their hardware-based counterparts, have concentrated on facilitating self-rehabilitation. A study used the developed software with Phantom Omni® to enable stroke patients to conduct wrist motor exercises at home, yielding favorable results [16]. Later, a home-based therapy system, comprising a cost-effective 6-DOF haptic device and a virtual reality game was presented [17]. This system facilitated fine motor skill rehabilitation and implicit learning. One of the games being developed and tested was "Space Explorer," which entailed following straight lines to engage and complete seemingly repetitive tasks.

Many sources in the literature have presented evidence supporting the idea that incorporating haptic technology into rehabilitation systems holds significant promise. However, designing a rehabilitation system for stroke patients is an even more critical and challenging task than its subsequent implementation. When developing a rehabilitation system for patients who have suffered strokes, many variables must be considered to identify the necessary design requirements. A study suggested that valuable insights could be drawn from specialists in occupational therapy (OT) and physical therapy (PT) [18]. In this work, Arabic language support, user comfort, and elderly accessibility were among the key functional requirements.

Later, a research team collaborated with healthcare experts to design games specifically tailored to promote and aid the healing process [19]. These low-cost rehabilitation games utilized haptic devices and could be enjoyed by the entire family, resulting in cost and time savings. The games, featuring a spider character named Anancy, were organized into three tiers, each with distinct rules and difficulty levels. Gamification techniques were incorporated, including level scoring and competitiveness, were incorporated, allowing healthcare providers to record patient scores, force exertion, and speed [20].

In many fields of regenerative medicine, haptic devices have aided in the recovery of stroke patients in hospitals and clinics. In addition to modern technologies, the participation of family members and healthcare professionals is crucial in physical therapy. However, crucial design requirements for haptic-assisted systems have often been neglected in previous research. This research aims to examine the design requirements provided by occupational therapists, physicians, and engineers to develop haptic-integrated software that facilitates a wide range of treatment alternatives. It should also enhance user-friendliness and allow additional rehabilitation scenarios in the future.

3. Methodology

To develop an effective rehabilitation program, we have divided the process into three main parts. As shown in Figure 1, the processbegins with the development of a questionnaire to explore the desired functions of the software, followed by software development, and pilot testing with users.

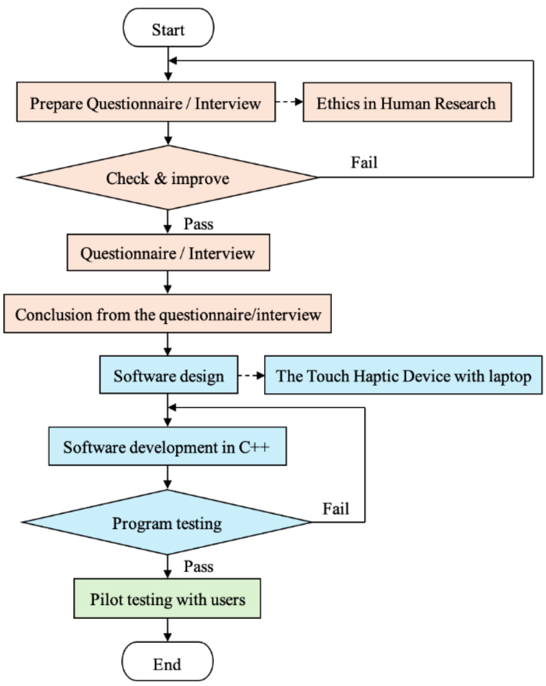


Fig. 1 A flow chart of the process

3.1 Design requirements / desired functions of the system

Initially, a questionnaire was initially created based on the related literature. It was then thoroughly reviewed and refined by an experienced medical professional. The final version of the questionnaire was then submitted to target samples including physicians, therapists, nurses, stroke patients, and their families. The purpose of this survey was to collect general information and explore correlations between personal characteristics and treatment designs. It was also designed to assess the functionalities of existing rehabilitation programs using the Likert scale and ranking questions. The Likert scale is a tool for respondents to indicate their level of opinion on closed-end questions. There are five options for respondents to select based on their level of agreement with each questionnaire item. For ranking question, optional answers allow respondents to present their opinions by indicating their preferences for each issue. These questions require respondents to enter numbers in order of importance from most critical to lowest. The most important rank refers to critical, high, moderate and the least important is low, respectively. The questionnaire consisted of four parts including medical requirements, software requirements, user performance measurements, and respondent recommendations.

The first section investigates therapeutic exercises tailored to meet the specific health needs of patients. These activities include drawing simple shapes, writing native letters, and playing games such as navigating a ball through mazes. Also, the investigation aims to explore the needs of distinct difficulty levels and the associated benefits.

The second section examines a variety of desired features embedded in the rehabilitation system environment. Such features include both visual and auditory functions that enhance patient enjoyment. Additionally, the study includes force feedback to provide a tangible and tactile experience.

The third section focuses on the performance measurement of the users. With the haptic system capabilities, it is now possible to evaluate kinematic parameters related to hand motion that cannot be achieved with traditional rehabilitation methods. These quantitative parameters, as shown in Table 1, include time, displacement, velocity, and jerk metric. Obtaining the data may help in effectively assessing the efficacy of current rehabilitation activities and designing better training methods.

Table 1 Definitions of user kinematic parameters

Parameters	Definitions
Time (s)	Duration required by a patient to complete a minor task.
Displacement (mm)	Quantification of manual dexterity by assessing the spatial displacement of a patient's hand along the XYZ axes.
Velocity (mm/s)	The pace at which a patient accomplishes a minor task.
Jerk metric (mm/s^3)	A quantifiable parameter employed to evaluate the fluidity of movement, obtained by averaging the rate of acceleration change during motion.

The concluding section of the survey provides an opportunity for respondents to express their preferences and suggestions regarding additional features they would like to see incorporated into future developments of the rehabilitation program. It is important to note that these recommended functions may or may not currently be available in the existing software.

3.2 Software development

3.2.1 Inclusion of haptic feedback

The Touch^{TM} haptic device as shown in Figure 2, is used, and integrated into the software environment to provide force feedback to the user's hand. This device allows users to feel virtual items and experience realistic touch sensations while interacting with 3D objects on-screen. The device has a pen, called a stylus and the force feedback workspace measures > 431W x 348H x 165D mm with three degrees of freedom (x, y, and z). It features a nominal position resolution of approximately 0.055 mm and a maximum exertable force of 3.3 N at the nominal orthogonal arm position [21].

Fig. 2 The Touch^{TM} haptic device

3.2.2 Software design

Customized software means software that is specifically and systematically developed or modified to meet certain users' needs. The design process for such software may consist of studying and understanding user needs and then developing software to meet those needs by focusing on precision in creating what users want. This approach helps ensure a good user experience, reducing mistakes and increasing satisfaction with the program.

The design of the prototype software in this study was developed based on the responses to the questionnaire in the previous step. The preferred functions of the software were derived from the results of the questionnaire through data analysis. In this software, the primary functions are divided into two main parts: the program structure and evaluation indicators. More details on the software design are presented in the following sections.

3.3 Pilot testing with users

A test of the developed software was conducted on healthy volunteers to evaluate its performance, particularly focusing on the included desired functions. A measurement and data recording feature were also included to improve its efficiency before conducting tests with stroke patient volunteers in future work.

Ten healthy volunteers were recruited for this research, all of whom were all right-handed. In this test, volunteers were required to use the provided stylus to trace various lines (straight lines, circles, squares, and triangles) displayed on a computer screen. When the volunteers begin drawing lines, the software automatically records measurement data such as time, velocity, displacement, acceleration, and jerk metric. Each volunteer was allowed to draw the displayed shape for no more than 30 minutes per day. They were given two practice sessions before the actual measurement and were required to complete the test three times during the pilot study.

4. Results and Discussion

4.1 Desired function assessments

Before distributing the questionnaires, the reliability of the questionnaire was assessed using Cronbach's Alpha coefficient. It was found that the Cronbach's Alpha coefficient was 0.863, which was greater than 0.70. This indicates that the questionnaire is suitable for the survey. This study was approved by the Khon Kaen University Ethics Committee for Human Research based on the Declaration of Helsinki and Clinical Investigation of Medical Devices for Human Subjects – Good Clinical Practice.

The questionnaire, including both quantitative and qualitative questions, was distributed to 30 target participants including medical staff, engineers, stroke patients, and their families. We chose the respondents by taking into account the feedback from all stakeholders including medical staffs, engineers, and stroke patients and their families. Medical staff provided essential information based on their experience in patient care. Engineers presented the technical issues on the important program functions and other elements. Stroke patients shared information on their actual demands, while their families provide further perspectives on daily use. Gathering feedback from all these groups ensured we could develop a comprehensive system satisfied everyone's needs. A total of twenty-four responses were returned (80%). The respondents comprised 6 males and 18 females (75%); approximately 41.7% of them were between 20 and 30 years old. The largest professional background group was composed of physical therapists (25.0%), followed by nurses (20.8%). A significant portion of the respondents had a 16 minimum of 16 years of work experience (29.2%).

In this survey, the primary topic that needed to be discussed was "medical requirements" for the rehabilitation program. Most respondents agreed that the program should start with basic training, including various line patterns (straight, zigzag, curves), which are crucial for hand and finger rehabilitation. They also mentioned the importance of exercising hand and finger flexion by drawing therapeutic lines. Advanced training would involve more complex shapes such as geometric figures, Arabic and Thai numbers, and letters. The highest level of agreement was found among 41.67% of the respondents, with a mean Likert score of 4.17, indicating strong consensus. A significant number of respondents emphasized the importance of a 2D line pattern in hand rehabilitation, rated at a critical level by 9 individuals (37.50%), and at a high level by 2 individuals (6.25%). Following closely is the geometric pattern, rated at a critical level by 6 individuals (25%) and at a high level by 4 individuals (16.67%). The pick & lay pattern was considered the least beneficial for patient hand rehabilitation, with 9 individuals (37.50%) rating it below the low level. Figure 3 illustrates a variety of training features based on medical requirements.

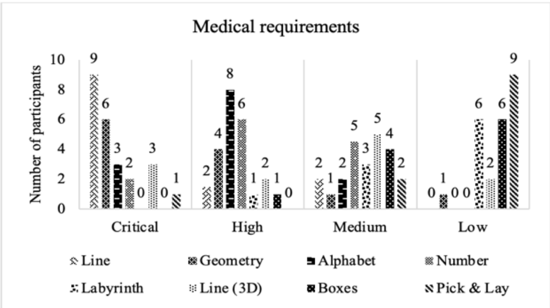


Fig. 3 Survey results for training features ranked from critical to low-level medical requirements**.**

Regarding software requirements, respondents ranked a combination of image, sound, and force feedback as the most important features, followed by a combination of image and sound. This preference is most likely due to its ability to enable users to experience tactile sensation, intuitively carry out rehabilitation activities, and thus accelerate their learning curve. Including images and sound, even without forced feedback, is important as they enhance patient enjoyment, relaxation, and overall training effectiveness. The obtained data revealed a high agreement rate (91.67%) with the visual, auditory, and tactile elements of the rehabilitation program. The mean Likert score of 4.92 indicated a strong consensus. Most respondents considered the visual, auditory, and tactile components as the most effective for hand rehabilitation, rated at a critical level by 16 individuals (66.67%). The image component alone was perceived as the least effective, rated at a low level by 15 individuals (62.50%). The data are shown in Figure 4.

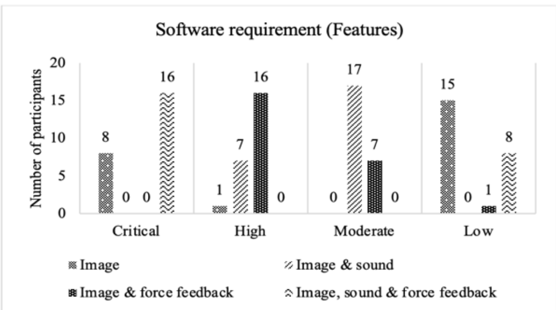


Fig. 4 Survey results for software features ranked from critical to low-level requirements.

Key performance measurements and kinematic parameters such as time, displacement, velocity, and jerk, are crucial for assessing patient performance and the effectiveness of haptic-based rehabilitation programs. These metrics provide insights into the range of motion, muscle strength, and task performance capacity, reflecting the patient's healing progress. Respondents highly valued these metrics for hand rehabilitation assessment, with a consensus level of 79.17% and a mean Likert scale score of 4.75. Time, displacement, velocity, and jerk were considered the most effective measures, rated at a critical level by 16 individuals (66.67%). Time and displacement, on the other hand, formed the least desired pair, rated at a low level by 17 individuals (70.83%). The data are shown in Figure 5.

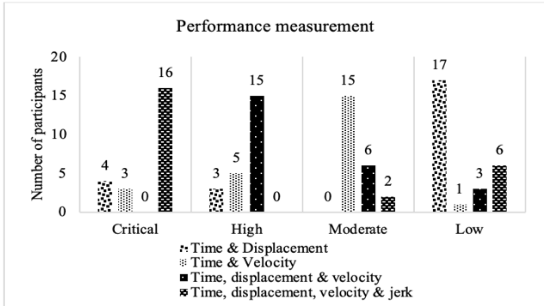


Fig. 5 Survey results for user performance measurements ranged from critical to low-level requirements.

In comparison with previous research (as shown in Table 2), the results from our study show that image and sound, as well as time and velocity, are important for rehabilitation systems. This is consistent with the findings from the previous studies. On the other hand, features that need to be emphasized should be design requirements from healthcare professionals or related personnel, including level, displacement, and jerk metrics. Moreover, it is essential to establish a hierarchy to determine the most critical aspects to improve the efficacy of the rehabilitation system.

Table 2 Comparison table of design requirements between previous research and this study

Authors	Customer			Features		Kinematic parameters				Rank
	A	B	C	D	E	F	G	H	I	
Afzal et al.[8]				✓		✓	✓	✓	✓	
Yang et al.[14]				✓		✓	✓			
Pareek et al.[17]				✓	✓	✓		✓		
Almousa et al.[18]	✓			✓	✓	✓	✓			
Auguste-Ramperad et al.[19]	✓			✓	✓	✓		✓		
Zbytniewska et al.[20]		✓				✓		✓		
This research	✓	✓	✓	✓		✓	✓	✓	✓	✓

A = Medical staffs, B = Engineers, C = Stroke patients & their families, D = Visual & sound, E = Level, F = Time, G = Displacement, H = Velocity, I = Jerk

4.2 Software development

4.2.1 Software design

We summarized data from the respondents and used the acquired data to develop software using the C++ language in Microsoft Visual Studio 2022. Images and displayed data were rendered with OpenGL. The developed software consisted of four images: straight line, circle, square, and triangle. Certain properties were also included such as setting view, rotation, defining haptic workspace, and changing background and object colors. Figure 6 shows a screenshot of the software. Lastly, the following force feedback features were made available for selection.

-Damping: Decreases vibrations in the system, which improves the system's stability and accuracy

-Friction: Creates resistance caused by movement between the surfaces of objects which causes a reduction in speed or movement that occurs

-Stiffness: Resembles a hard surface with pressure resistance to keep the object flexible through the application.

-Magnetic: The tip of the stylus is attached to the object and also makes it easier to record data.

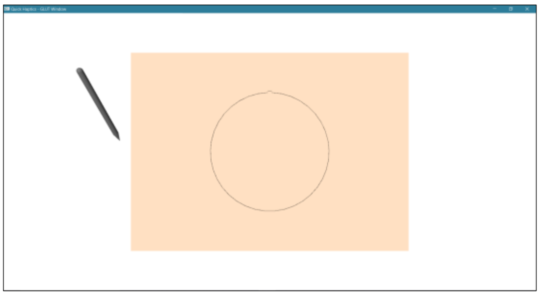


Fig. 6 Screenshot of the developed software

4.2.2 Evaluation indicators

To assess hand movement performance, we developed a specific code to simplify real-time data collection and automatically store the results in *.txt format. The software includes a complete calculation module that serves parameters including time, displacement, velocity, and jerk. The parameters are defined as follows:

(i) Time (s) is when the patient interacts with different patterns and is an important parameter that can indicate the speed of a patient’s movement. Time also indicative of recovery speed, hand control improvement, strength, and endurance.

(ii) Displacement (mm) is measured between two location, which informs the patient where to draw a line to determine the new position and the distance from the established pattern. This parameter indicates the distance that a patient can move while tracing a pattern displayed on the screen.

(iii) Velocity (mm/s) is the patient’s movement speed based on their movement distance per training session. Velocity is also a parameter that can indicate hand movement performance during rehabilitation, such as motor control, muscle strength and endurance, muscle coordination, flexibility and agility, functional performance, and neurological recovery.

(iv) Jerk (mm/s^3) is a parameter used to average the rate of change in acceleration in movement [22]. Jerk can indicate smoothness of movement, in which a decrease in the jerk value indicates better muscle coordination and that the patient can use their hands more effectively. Each movement requires improved coordination between distinct muscles. For movement control, a lower jerk value suggests greater control over the movement. Patients can move their hands more steadily. Vibrations and jerks are reduced. This indicates that the muscles and nervous system are recuperating well. It is defined as follows:

$$J_M = \frac{\Delta a}{\Delta t} \quad (1)$$

Where J_M is the rate of change in acceleration, Δa is a change of time, and Δt is a change in time.

All software commands were set up to communicate with the connected haptic device. Once the software was completed, the developed software was tested by both the developer and doctors. Valuable suggestions were provided to improve and correct the software before testing the program with a group of volunteers.

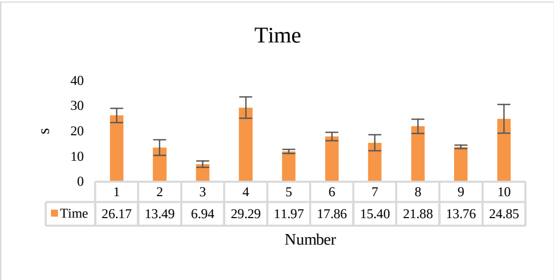
4.2.3 Pilot study with users

We tested the program using a sample of ten healthy volunteers, comprising two males (M) and eight females (F), with ages ranging from 20 to 80 years and a mean age of 48.40 years. Subsequently, we assessed the outcomes, including time, displacement, velocity, and jerk. The three tests performed on each volunteer were averaged, as shown in Table 3.

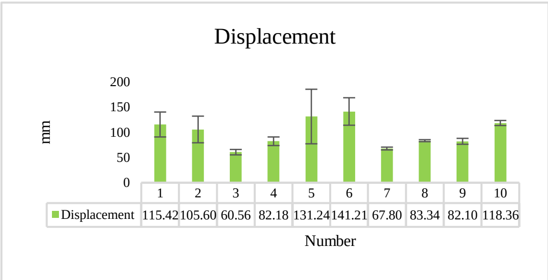
Table 3 User information and recorded results from Pilot Test

No.	Sex	Age	Time (s)	Displacement (mm)	Velocity (mm/s)	Jerk (mm/s^3)
1	F	50	26.17	115.42	5.82	252.15
2	M	45	13.49	105.60	10.16	4458.56
3	F	42	6.94	60.56	9.92	1165.85
4	F	45	29.29	82.18	4.28	2819.13
5	F	46	11.97	131.24	14.95	5073.01
6	F	56	17.86	141.21	11.61	5225.54
7	F	52	15.40	67.80	6.32	2923.61
8	F	57	21.88	83.34	5.17	2059.58
9	F	25	13.76	82.10	7.66	2757.28
10	M	66	24.85	118.36	6.58	3367.39
Average		48.40	18.16	98.78	8.25	3010.21
SD		10.93	7.15	27.43	3.35	1612.74

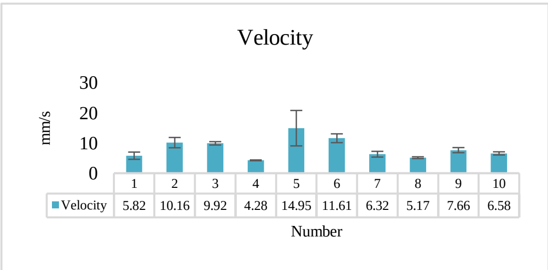
We calculated the average values for each parameter among the ten volunteers: the average time was 18.86 s, displacement was 98.78 mm, velocity was 8.25 mm/s, and jerk was 3010.21 mm/s^3. Additionally, Figure 7 shows the standard deviation (SD) from three tests conducted on each individual, from person one to person ten. There are a total of four assessments: time (Fig. 7a); displacement (Fig. 7b); velocity (Fig. 7c); and jerk (Fig. 7d). The figure reveals varying standard deviation values among individuals, indicating differing levels of data variance. High standard deviation suggests considerable variability in the data, whereas low standard deviation signifies less data dispersion or consistency. This variability could stem from factors like variations in how the stylus of the haptic device is held during each test, which affects the results. Moreover, differences in hand movement abilities among individuals contribute to variations in parameter measurements. Despite similar ages, the measurement results for various parameters exhibit disparities.



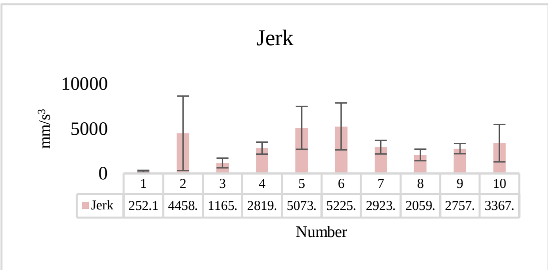
a) Time



b) Displacement



c) Velocity



d) Jerk

Fig. 7 The results of the circle from volunteers: a) time; b) displacement; c) velocity; and d) jerk

5. Conclusion and Future Work

This research aimed to identify the essential design requirements for a customized haptic-assisted hand motor training system designed specifically for stroke patients. Valuable insights were collected through comprehensive surveys and in-depth interviews involving a diverse range of healthcare professionals, engineers, stroke patients, and their families. The program's key components were ranked, with force feedback, image, and sound emerging revealed as the most critical factors. Measurement parameters such as displacement, time, velocity, and jerk metrics were recommended to evaluate the program's effectiveness and track patients' progress. The survey participants strongly emphasized the importance of incorporating a finger grip on the haptic stylus grip to ensure a comfortable and effortless grasp. They also suggested including games with varying difficulty levels to enhance patients' hand-motor skills. The research proposed additional features and emphasized the significance of visual perception and visual motor integration in augmenting the rehabilitation experience. The findings and recommendations derived from this research will play a pivotal role in advancing the proposed rehabilitation system.

After using the software, we conferred with the group of volunteers to gather their feedback. Most participants expressed satisfaction with the developed system, especially its efficiency in providing quick results and assessments, as well as facilitating immediate understanding of the results. This will be quite helpful when applied to patient populations. Nevertheless, there is room for improvement though, particularly in terms of evaluation indicators such as developing a function to automatically measure the error when the drawn lines do not match the lines of the image in the program. Our next step is to develop more complex software to measure and record hand movements with errors in real-time during rehabilitation activities, followed by testing the software with stroke patients.

Acknowledgements

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