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Original Article

System Based on Haptic Technology for the Rehabilitation of Patients Suffering from Wrist Injuries

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Abstract - *According to the World Health Organization (WHO), in 2021, around 1,710 million people will have musculoskeletal disorders (MSDs). Two of the most common MSDs are carpal tunnel syndrome and tendinitis, which affect the wrist. Haptic technology has been applied in the area of medicine, especially for the rehabilitation of patients. The main objective of this study is to develop a haptic system composed of the Novint Falcon robot, a rehabilitation routine composed of 3D objects designed in H3DAPI so that the user can visualize and interact with the proposed activities and thus develop physical exercises for rehabilitation. The system was tested with ten participants, five of whom had previously suffered a wrist injury. In addition, six participants indicated that the degree of difficulty in using the haptic system was "Easy", and three indicated it was "Very Easy". Ten participants indicated that they consider it positive to add a playful factor to the rehabilitation routine. Finally, the most preferred activity by the participants was the sports activity (9 participants), and the least preferred activity was precision (6 participants).*

Keywords - *Musculoskeletal disorders, Tendinitis, Carpal tunnel syndrome, Haptic technology, Novint Falcon, 3D modeling.*

1. Introduction

Musculoskeletal disorders (MSDs) comprise more than 150 disorders in the joints or other tissues, such as muscles, tendons, ligaments, nerves, and discs. Which mainly affects the back, neck, shoulders and upper or lower extremities [1].

The leading causes of MSDs are related to work tasks, when a person is exposed to several risk factors [2,3], such as repetitive movements, forced postures, sedentary position for a long time, very long hours, lack of rest, medical history and lifestyle.

Because the wrist connects the hand with the forearm, it must have the ability to be flexible, which is why it is made up of minor joints, which makes it more prone to different types of injuries and diseases. The most typical injuries and diseases of the wrist are the following: fractures, tendinitis, sprains, strains, gout, ganglion cyst, carpal tunnel syndrome and osteoarthritis [4]. Besides, the most common musculoskeletal disorders are two wrist injuries, such as carpal tunnel syndrome and tendinitis [3].

According to the World Health Organization (WHO), by 2021, around 1.71 billion people worldwide will have musculoskeletal disorders (MSDs) [5]. In the region of the Americas for 2019, a prevalence of 22.4 thousand cases per 100 thousand inhabitants was reported [6].

The occurrence of MSDs causes persistent pain, limited mobility, and impaired dexterity, which is why the capacity of people affected by MSDs is reduced. For this reason, according to the WHO, musculoskeletal disorders are the main factor contributing to the need for rehabilitation worldwide [2, 6].

Furthermore, haptic devices are mechanical input-output devices that mediate between the computer and the end user. The haptic device inputs the user's physical manipulation of 3D objects on the screen. As its output, the device will provide force feedback to the user's hand, allowing them to feel virtual objects and produce real tactile sensations [7].

Haptic technology has various applications, such as education, training, art, design, entertainment, and medicine [8]. Regarding medical applications, haptic devices can be used to rehabilitate patients. For example, in [9], in the case of wrist injuries after surgery or trauma, it was proposed to develop a low-cost haptic system to improve the movement and grip of the patient's wrist. The system was composed of the Novint Falcon device, a haptic device primarily used in the video game industry, and a glove with three inertial sensors capable of capturing the orientation of the wrist. The system was tested with ten therapy-naïve outpatient stroke patients for six weeks. Finally, a recovery in patients' hand functions was observed, and an average reduction of 70% of errors in their activities was reported. As shown, haptic technology is more efficient than physiotherapy, orthoses or additional surgical interventions.

Moreover, in [10], it was observed that spinal cord injury (SCI) produces physical disability in patients who suffer from it. Given this, it was proposed to take advantage of virtual reality systems and haptic devices to provide a rehabilitation alternative for upper limbs. The system consists of the Novint Falcon robot, which will provide haptic feedback and a Myo Gesture bracelet which will collect electromyographic signals from the arm. The rehabilitation exercises are given through three virtual reality games where the variable evaluated is smoothness (characteristic of a skillful and well-coordinated human movement). The proof of concept carried out shows that the virtual scenarios can be personalized for each patient and that the design of this system generates an excellent haptic response and reliable monitoring of arm muscle contractions.

Finally, in [11], it was observed that neurological disorders are the primary sources of motor disability. Also, it was observed that the hospital environment generates demotivation and little interest in patients when performing the exercises, which generates poor rehabilitation. Therefore, a rehabilitation system was developed through games using a haptic device (Lambda Health System), virtual reality, and a head-mounted display (HMD). The virtual reality system maintains the patient's attention during the treatment, while the haptic system gives force feedback to the lower limbs and is the game's controller. This system was tested by 33 health specialists and rehabilitation experts (physiotherapists, occupational therapists, physical medicine and rehabilitation doctors), among others. After a survey, the results showed great enthusiasm on the part of health specialists, who indicated that the system has proven to be an effective tool for health and has solid potential in the field of rehabilitation.

Given the problems mentioned earlier and observing that haptic technology can be used for rehabilitation, the main objective of this study is to develop a system based on haptic technology for rehabilitating patients suffering from wrist injuries. The haptic system proposed has the following elements: a PC, Novint Falcon, Force Dimension SDK, a driver to control the haptic and robotic functions of Novint Falcon, the H3DAPI interface to visualize and interact with 3D objects included in three activities proposed as part of a rehabilitation routine for this type of injury. System tests were carried out, and a questionnaire was used to measure users' satisfaction.

This system is of paramount importance because musculoskeletal disorders affect the wrist and limit a person's dexterity and mobility. In addition, in chronic cases, due to the lack of attention, rehabilitation and treatment of this type of injury, permanent disability can occur that could cause job loss, early retirement, decreased quality of life and lack of autonomy or economic independence.

2. Wrist Injuries

The various activities that human beings carry out daily, from sports to sleeping habits, have a level of risk directed at the wrist [3]. Among the most common is gout, caused by the increase in uric acid in the form of crystals, causing pain and swelling that can even harm the joints of the fingers [12].

Another common problem in MSDs is arthritis, since according to the CDC, by 2040, 26% of the world's population will have some condition related to arthritis [13]. This disease, when found in the wrist, is the cause of an enormous number of medical consultations with rigorous and constant treatments.

In addition, another bulk of the population suffers from wrist problems after a fracture or direct injuries to the arm, such as car accidents [14], falls or sports. They are accompanied by considerable pain and restriction of certain activities that do not allow them to lead a life in the usual way.

In the present research, two common wrist injuries will be addressed, such as carpal tunnel syndrome and tendinitis.

Carpal tunnel syndrome is a common and disabling condition where the median nerve is damaged by excess pressure within the carpal tunnel, as seen in Fig. 1 [27]. Its most common cause is associated with tasks requiring repetitive hand movements. Besides, it occurs more frequently in women between 40 and 60 years [16].

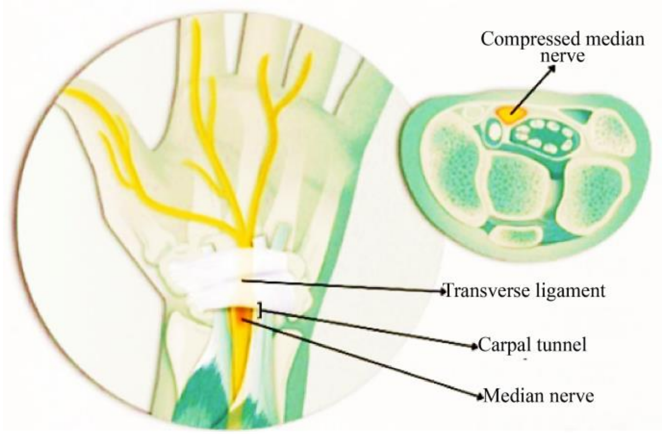

Fig. 1 Carpal tunnel syndrome

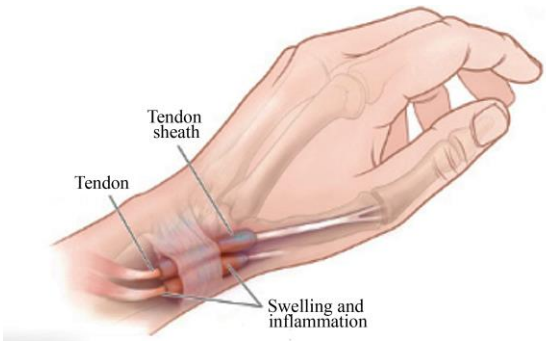

Fig. 2 Tendinitis

Likewise, tendinitis is an inflammation that affects any tendon but frequently affects the sheaths of the tendons in the wrist and fingers, as can be seen in Fig. 2 [17].

Tendinitis is caused by overexertion and affects adults over 40 years, as their tendons are less tolerant to stress and less flexible. According to the Bureau of Labor Statistics, tendinitis causes more than 70,000 people to miss work yearly [18].

3. Haptic System for Wrist Rehabilitation

3.1. Haptic System

The design of the proposed haptic system is given as follows:

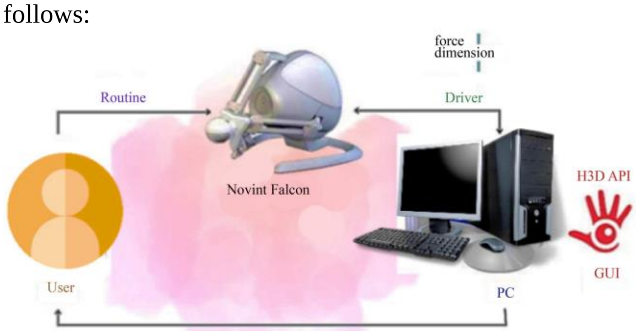

Fig. 3 Diagram of the haptic system

As can be seen in Fig. 3, the haptic rehabilitation system is made up of three main elements: a haptic device (Novint Falcon), a PC where the virtual environment is located, and finally, the user, who will be the operator who closes the system. Each main element of the system is described as follows:

3.1.1. Controller

The Force Dimension SDK software allows us to use the robotic and haptic functionalities of the Novint Falcon and also allows us, through other platforms, to perform haptic visualizations.

3.1.2. GUI

The H3DAPI software allows us to design, visualize and interact with 3D objects as a part of the rehabilitation routine on the PC in a more user-friendly environment.

3.1.3. Routine–user

Through the grip of the Novint Falcon, the user can maneuver and interact with the activities proposed in the routine and meet their objectives.

3.2. Novint Falcon

Novint Falcon is a three-dimensional haptic device with motors dedicated to each dimension. Designed by Novint Technologies Inc. and licensed from Force Dimension haptic technology, Novint Falcon was released in June 2007 and became the world's first 3D consumer haptic device for entertainment. This robotic controller has high fidelity as it has patented mechanisms and sensors that allow haptic and sensory immersion [28].

Fig. 4 Novint Falcon

Novint Falcon's technology allows users to get a detailed 3D feel of the shape and texture of objects. The specifications of the said controller can be seen in Table 1 [20].

Table 1. Novint Falcon specifications

Specifications		Unit
DOF* input	3DoF*	x-y-z
DOF* output	3DoF*	x-y-z
3D Touch Workspace	101*101*101	mm
Resolution	0.05mm	mm
Response time	8	ms
Maximum force	8	n/mm
Minimum force	4.4	n/mm
Power	30	Watts
Voltage	100 – 240V	Volts
Frequency	50 – 60	Hertz
Weight	2.75	Kg

**DoF: Degrees-of-Freedom*

As can be seen, the Novint Falcon controller has three degrees of freedom that include left-right, forward-backwards and up-down movements [21].

Besides, Table 2 shows the minimum requirements for the connection of Novint Falcon with the computer:

Table 2. Recommended requirements

Processor	2.4 Ghz
OS	Windows XP Service Pack 2, Windows Vista
Graphic Card	256 Mb 3D hardware accelerated graphics card
Hard Drive	1.5 Gb free disk space
Memory	1 Gb RAM
USB	2.0 connection
Other	Broadband Internet Connection

Table 3. Computer specifications

Processor	Intel Core i5-6500
OS	Windows 8.1 Pro
Hard Drive	234 GB free disk space
Memory	8 GB RAM
USB	2.0 connection

In the present study, the Novint Falcon model was used with the basic implementation of the device and a computer (PC) capable of generating communication between this haptic device and the required processes. In Table 3, the characteristics of the computer used in the present study can be observed:

3.3. Rehabilitation Routine

In order to establish an adequate rehabilitation routine with the Novint Falcon, the routines of different physiotherapists were evaluated for carpal tunnel injury and tendinitis [23, 24, 29]. After evaluating them, it was observed that there are six movements (Fig. 5) that are the base of these exercises: up-down, right-left and forward-backwards:

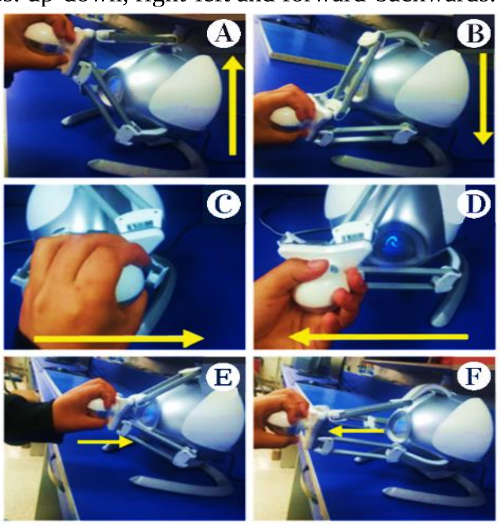

Fig. 5 Routine moves with the Novint. A) Up, B) Down, C) To the right, D) To the left, E) Forward, F) Backwards

Moreover, if these routines are accompanied by an object (especially a sphere), the exercises become even more bearable. Since the Novint grip handle is spherical, it serves as a support point for the wrist, which will be beneficial for the user to perform the routine with greater comfort.

Three activities are proposed to compose the rehabilitation routine; the objectives and movements worked on for each activity are observed in Table 4:

Table 4. Recommended requirements

Activity	Objective	Movements worked
Precision	Touch the exact center of the 3D sphere to enlarge the image. Degree of difficulty: Medium.	Strengthens the person's precision and practices back-and-forth movements.
Jenga	Remove as many pieces of the same color as possible without causing the tower to fall. Degree of difficulty: Medium/high.	The movements of left-right- and forward-backwards are worked.
Sports	Prevent the ball from leaving the field and score points. It has three degrees of difficulty and game styles (rebound, score and precision).	All movements are worked: Up-down Right-left Forward-backwards.

The duration of the rehabilitation routine is defined between the ranges of 10 to 15 min to avoid causing pain or overloading the user's wrist. Nevertheless, it is also a parameter that will depend on how the patient progresses with the proposed routine.

3.4. Graphical User Interface (GUI)

The design of each proposed routine was developed in the H3DAPI software, an open-source API that allows us to handle scenes with graphics and haptics [25]. Likewise, the programming languages X3D and Python were used. Table 4 shows a detailed description of each activity that is part of the rehabilitation routine:

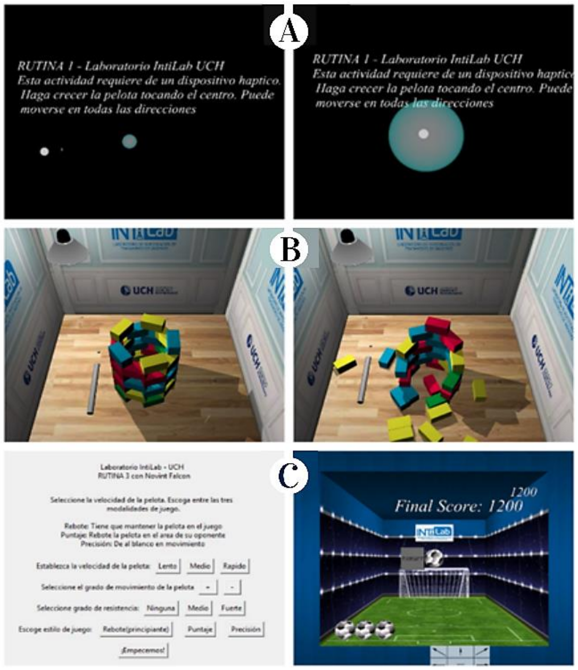

Fig. 6 Implementation of the rehabilitation routine. A) Activity 1: Precision, B) Activity 2: Jenga, C) Activity 3: Sports

In the present work, the routines contemplated a playful factor, as seen in Fig. 6, since it generates a more pleasant and friendly environment for the user. It is an essential factor for the user to complete the routine satisfactorily. This idea was reinforced by the research works [10] and [11], which state that playing games for rehabilitation generates a more significant commitment to complete rehabilitation in the patient.

4. Results and Discussion

Firstly, an application protocol was implemented to standardize the conditions for all the users who tested the proposed haptic system. The proposed protocol for carrying out tests has the following considerations:

Table 5

	Distance (cm)	Angle (°)
Desk depth	60	-
Novint location	35	45
Screen-User	50-70	0
Screen-Novint	20	45
Novint-User	40-50	45

As seen in Table 5, the considerations considered in the testing protocol mainly correspond to the distances and angles established to position the three main elements of the proposed system: the PC screen, the Novint Falcon and the user.

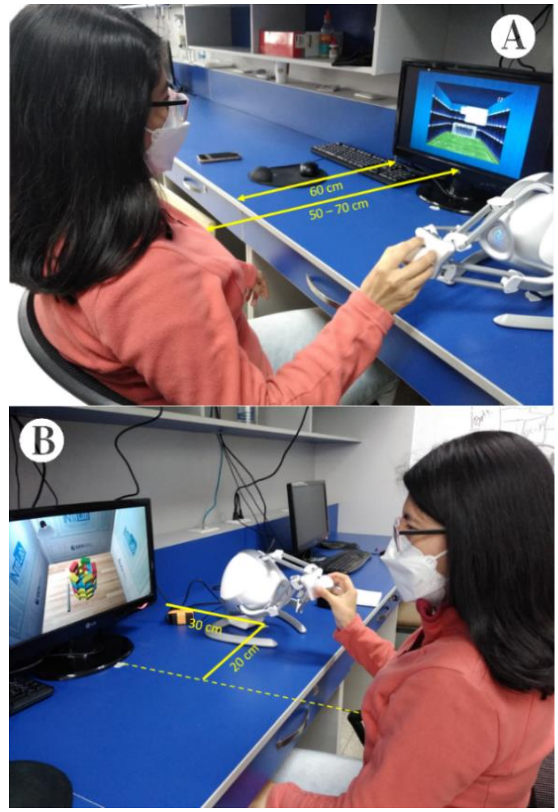

Fig. 7 Setting of the test protocol

Moreover, in Fig. 7, the configuration of the test protocol described in Table 5 and the start-up of one of the tests can be observed:

As seen in Fig. 7, a space clear of other objects was used to comfort the user. In addition, it is crucial to indicate that it was considered to use a chair with armrests for the user in order to support the user's arms and therefore provide greater comfort when interacting with the haptic system. Finally, the user was recommended to keep their arms parallel to the ground while performing the proposed routine.

The results obtained by applying the test protocol already described are detailed below.

Firstly, it is important to indicate that each user was asked to perform the three activities of the proposed rehabilitation routine using the haptic system, after which they were asked to answer a 17-question questionnaire in Google Forms.

The tests were carried out with a sample of ten participants, seven males and three females. All the participants are researchers and students of the institution where this research was developed. The following age groups were included:

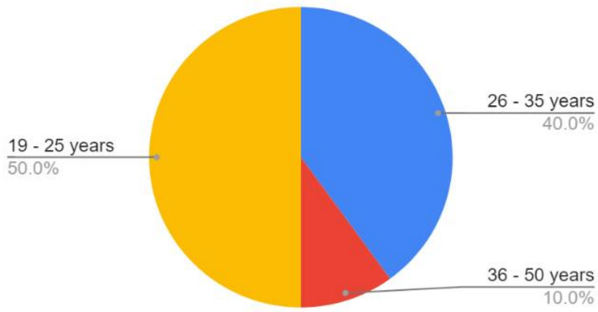

Fig. 8 Age groups of the participants

Of the sample evaluated, eight people indicated that their dominant hand was the right hand, and two indicated their dominant hand was the left. For this last group, the test setup had to be adapted, and the Novint Falcon had to be positioned to the user's left with the exact distance and angles established in the test protocol.

In addition, five of the participants indicated that they had previously suffered a wrist injury. In terms of the type of wrist injury, the following were mentioned:

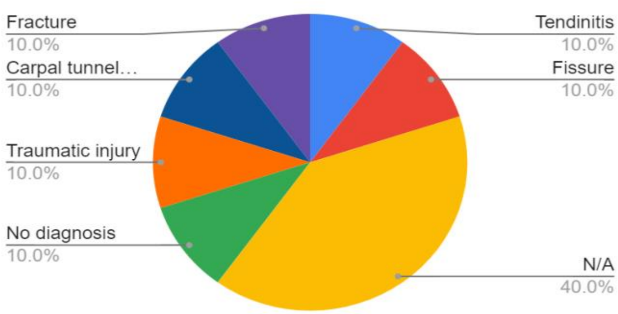

Fig. 9 Type of injuries reported by the participants

Likewise, two participants indicated that they had received physical rehabilitation to treat their wrist injuries. However, both indicated that it was not easy for them to complete the physical rehabilitation recommended by their doctor; among the reasons they indicated that the exercises were prescribed to be completed at home, which is why one of the participants indicated that he did not understand how he should do his exercises without accompaniment. Besides, the other participant indicated that he found the prescribed exercises boring and frequently forgot to do them. Finally, the remaining three participants indicated that their doctor had only prescribed anti-inflammatories and analgesics, not physical rehabilitation. However, they would prefer to be prescribed some exercise due to the type of pain and injury they presented. Perhaps it would have accelerated their recovery.

Furthermore, six participants indicated that they already knew about haptics technology, and the remaining four had not heard of this type of technology. Likewise, six of the participants indicated that their experience interacting with the developed haptic system was "Very good", and four participants rated their first experience as "Good". In addition, regarding the degree of difficulty in understanding how to manipulate the developed haptic system, these were the results obtained:

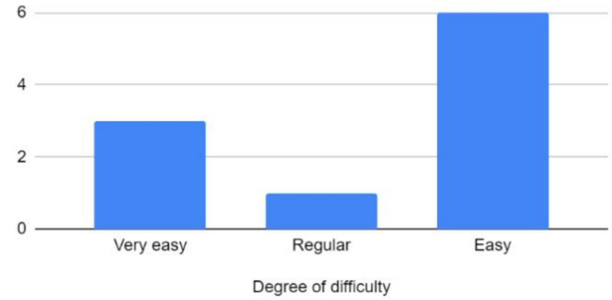

Fig. 10 Degree of difficulty in manipulating the haptic system

In addition, the ten participants indicated that they consider that adding a playful factor to rehabilitation routines can be positive for the patient. The keywords why they consider this are detailed in the following word cloud:

Fig. 11 Keywords mentioned by participants

As can be seen, the five keywords most mentioned by the participants when asked why our system was positive for the patient were: Entertaining, motivation, playful, de-stressing and interaction.

Also, when asking the participants if they considered that with the haptic system and the proposed rehabilitation routine, they could carry out the suggested movements to rehabilitate a wrist injury, the ten participants indicated that they considered it. For this reason, when asked what type of rehabilitation they would prefer to develop, nine participants indicated that they would prefer to perform physical rehabilitation using the haptic system. Otherwise, one of the participants indicated that he was indifferent, and neither of the participants chose to develop traditional physical rehabilitation.

Finally, the participants were asked which activities of the rehabilitation routine they preferred the most and which the least. The results obtained were as follows:

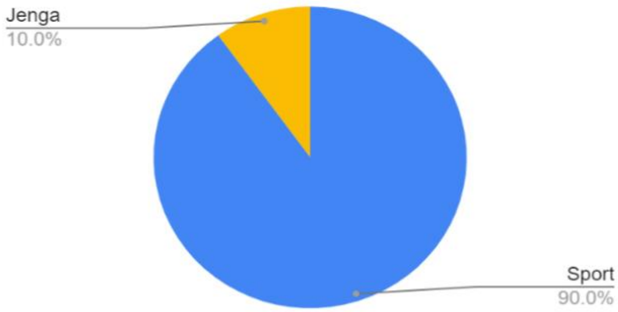

Fig. 12 Prefered haptic activity

As can be seen, the most preferred activity by users was sports, with nine participants indicating that they preferred it. This result was very positive since this activity was the one that contemplated the six central movements of the rehabilitation routine and different levels of difficulty and game modes.

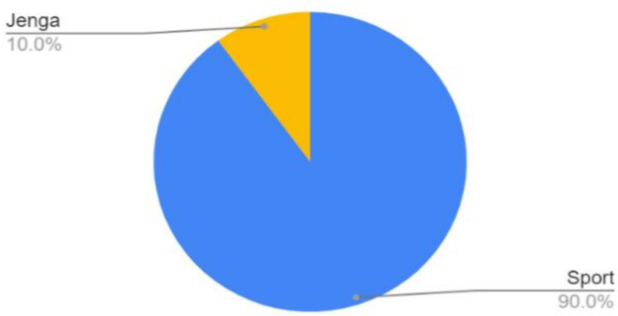

Fig. 13 Least preferred haptic activity

Finally, it was found that the activity the users preferred the least was the precision activity, with six participants indicating that it was their least preferred activity to perform within the rehabilitation routine.

5. Conclusion

It is observed that haptic technology can have multiple applications; in this case, an application in the health area was proposed since a haptic system was developed as a potential option for rehabilitating patients suffering from wrist injuries.

The system focused on two musculoskeletal disorders: tendinitis and carpal tunnel syndrome. Rehabilitation routines frequently used for the physical rehabilitation of both injuries were reviewed, and it was found that the central movements of these routines are: up-down, right-left and forward-backwards. These were the elements that were included in the proposed rehabilitation routine.

In addition, the design of the system consisted of the following elements: a PC, the Novint Falcon robot, a rehabilitation routine that consisted of three activities, Force Dimension that allowed control of the robot's functionalities, H3DAPI that allowed designing, visualizing and interacting with objects 3D that were parts of the rehabilitation routine and finally the user who shut down the system.

In order to test the functionality of the haptic system, tests were carried out with ten participants, of which seven were male and the rest were female. Mainly there was the presence of three age groups, the youngest of the participants was 19 years old, and the oldest of the participants was 37 years old. However, although the participants were young, five indicated that they had previously suffered a wrist injury.

The injuries suffered by the participants were: tendinitis, fissure, carpal tunnel syndrome, fracture and traumatic injury. Although five participants had suffered injuries, only two reported that they were recommended physical rehabilitation at home, which was challenging to complete due to a lack of support and carelessness. Something that should be addressed in a future study is that the rest of the participants who reported having an injury indicated that their doctor only prescribed anti-inflammatories and analgesics, not physical rehabilitation. However, physical rehabilitation would be necessary for adequate recovery due to the type of injury they presented.

Regarding their experience with the haptic system, six of the participants indicated that it was “Very good” and four participants as “Good”. Besides, ten participants indicated that with the proposed rehabilitation routine, they could carry out the recommended movements to rehabilitate a wrist injury. In addition, nine participants indicated that they would prefer to perform physical rehabilitation using the haptic system developed in the present study.

As can be seen, the developed system has the potential to be an option to propose physical rehabilitation, adding a playful factor for the patient, which can be a crucial aspect for patients to complete the physical exercises recommended by their doctor in an easy and fun way. As future work, it is planned to develop a longitudinal study with patients with a wrist injury to observe their potential degree of recovery.

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